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Ultrasonic Consolidation : Status Report on Development of Solid State Net Shape Processing for Direct Manufacturing

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ABSTRACT

Ultrasonic Consolidation is a solid state additive manufacturing process based on continuous ultrasonic metal welding. Metal foil layers are sequentially laminated to produce net shape objects from common engineering alloys. Most additive manufacturing processes use some form of material phase transformation to achieve the transition from a featureless feedstock to a fit-for-service geometry. This transformation puts practical limits on the range of materials that can be deposited. Ultrasonic Consolidation (UC) on the other hand, achieves laminar deposition using solid state bonding and so can be used in conjunction with a range of thermally delicate or non-equilibrium microstructured materials. This paper documents the status of the process, and some current and emerging applications

1.0 INTRODUCTION AND BACKGROUND

Most deposition processes use some form of material phase transformation to achieve the transition from a featureless feedstock to fit-for-purpose engineering article. Typically this involves a liquid-solid transformation, which puts practical limits on the range of materials that can be deposited. Ultrasonic Consolidation (UC) on the other hand, achieves laminar deposition using solid state bonding and so can be used in conjunction with a range of thermally delicate or non-equilibrium microstructured materials.

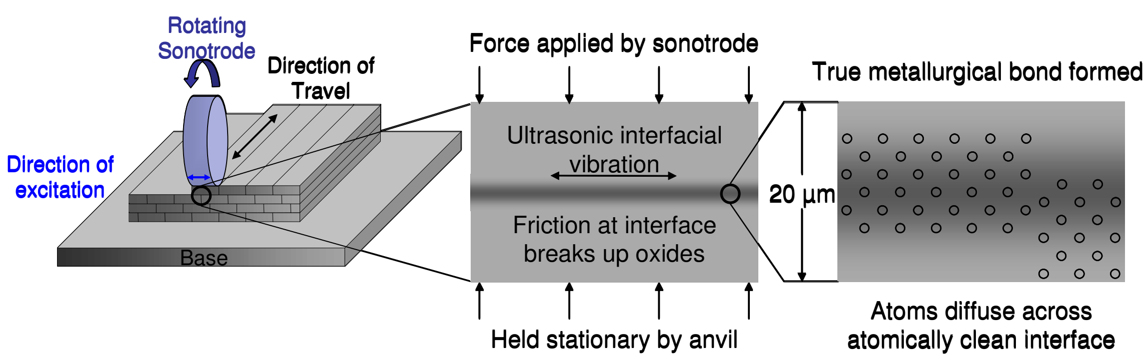

Figure 1. Ultrasonic Consolidation process schematic.

The Ultrasonic Consolidation process differs substantially from other direct metal additive manufacturing processes in that it applies the technologies of ultrasonic joining to produce true metallurgical bonds between layers of material without generating molten metal at the interface.

White, D.R. (2006) Ultrasonic Consolidation : Status Report on Development of Solid State Net Shape Processing for Direct Manufacturing. In *Cost Effective Manufacture via Net-Shape Processing* (pp. 21-1 – 21-12). Meeting Proceedings RTO-MP-AVT-139, Paper 21. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

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UC is a micro-friction process, the mechanics of which are schematically illustrated in Figure 1. During UC, the material being deposited is translated against the previously built volume at very high frequency and low amplitude. As this occurs, surface contaminants such as oxides are fractured and displaced, and atomically clean surfaces are brought into intimate contact under modest pressures at temperatures that typically do not exceed 0.5 Tm. Plastic flow occurs in a narrow interfacial zone about 10-20 microns in width, and recrystallization and grain growth proceed across the interface. A strong, featureless bond zone results, without the coarse, remelted zones characteristic of liquid phase direct metal processes. Oxides at the build material surface, and inclusions present in the build material are broken up and distributed in the bond zone. Figure 2 shows the microstructure across an interlaminar boundary following UC during a part build.

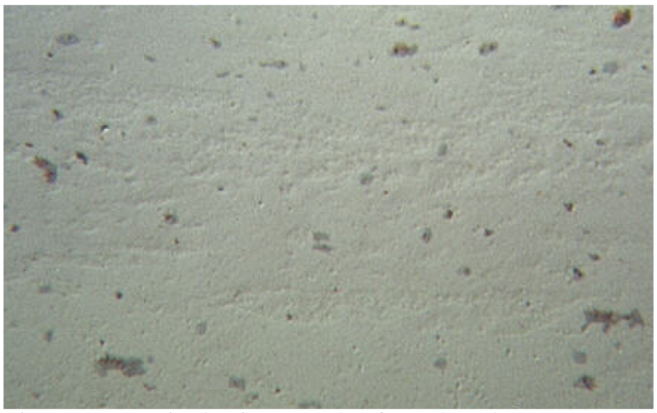


Figure 2. Optical micrograph of UC bond zone. 1000X

Solid state processing has a number of important benefits in direct manufacture of metal tooling and parts.

1. No safety hazards associated with the formation of liquid metal, metal fume, powder handling, dust or other molten metal handling problems.
2. No atmosphere control is required to address molten metal oxidation issues.
3. Low energy consumption, due to the low temperatures involved and small volumes of material actually affected metallurgically by the process.
4. Reduced residual stresses and distortion, because no liquid-solid transformation occurs, and dimensional changes during processing are substantially lowered.
5. Higher deposition rate because lower heat input per deposited volume means less time is required for heat dissipation.
6. Uniform article composition employing engineering alloys without infiltrants.

Because UC is a solid state process, it provides excellent potential as a means of fabricating multi-material and functionally gradient armor. Table 2 below [ref AWS Handbook] shows the material combinations that have been previously demonstrated to be suitable for use with ultrasonic metal joining technology.

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al Alloys	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be Alloys		●	●			●										●		
Cu Alloys			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe Alloys						●			●	●	●		●	●		●	●	●
Mg Alloys							●						●			●		
Mo alloys								●	●		●			●		●	●	●
Ni Alloys									●	●	●			●		●	●	
Pd										●			●	●				
Pt Alloys											●	●		●		●	●	
Si													●	●				
Ag Alloys													●	●				●
Ta Alloys														●		●	●	
Sn															●			
Ti Alloys																●	●	
W Alloys																	●	
Zr Alloys																		●

Table 1. Ultrasonic metal joining combinations. [1]

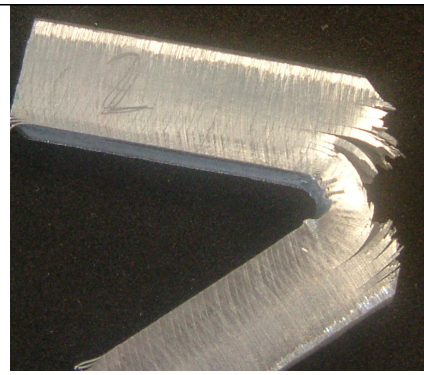
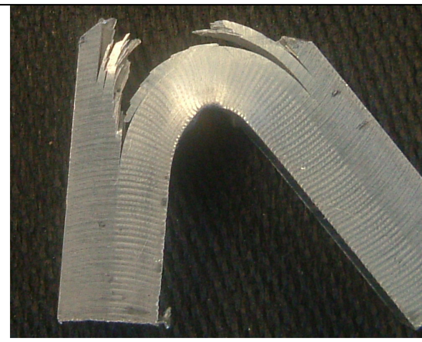
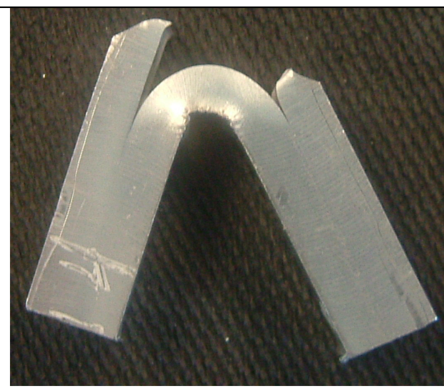
1.1 Preliminary Properties Data

Very limited tensile data has been obtained however, for 3003 H18, our standard build material for rapid prototyping, the following results were obtained on standard Charpy specimens using a simple, uninstrumented testing machine.

Table 2. Impact Results	100% laminar	50% laminar - 50% billet
6061 H-18	200 ft-lbs	197 ft-lbs
3003 H-18	173 ft-lbs	180ft-lbs

Preliminary Charpy testing has been conducted on some ultrasonically laminated specimens to illustrate this phenomenon. Several geometries were tested, the results are given in Table 3 below.

Table 3. Charpy Specimens		
Specimen type	Ft-lbs	result

100 % laminar	173	
50% laminar, notched laminate	180	
50% laminate, notched base	163	

Further testing is clearly needed. In Solidica’s historical rapid tooling market, these data were unimportant to the customer base. However, as applications in manufacturing and repair expand, there is an increased need for data, which Solidica is working to fulfill.

2.0 Current Applications

Solidica's initial application for UC is in the rapid prototyping and rapid tooling arena, with a principal focus on tooling. Recently a third party study was performed with Raytheon, Inc. on the use of UC in fabrication of tooling. These results were obtained on fabrication of mold for producing investment casting patterns. However, they are likely to be representative of results for aluminium tooling for vacuum casting, injection molding and other similar processes.

2.1 Tooling Case Study Results

The UC process was developed as a rapid tooling technology that combines the benefits of additive and subtractive machining to produce a "one button" system for fabricating tooling for processes such as vacuum forming, injection molding, etc. that typically require multiple machines (e.g., mills, EDM, etc.) and operators.

As a tooling process, UC embodies many principles of lean manufacturing, reducing multiple part programs, machines, and operators to one piece flow. This is illustrated in Figure 3.

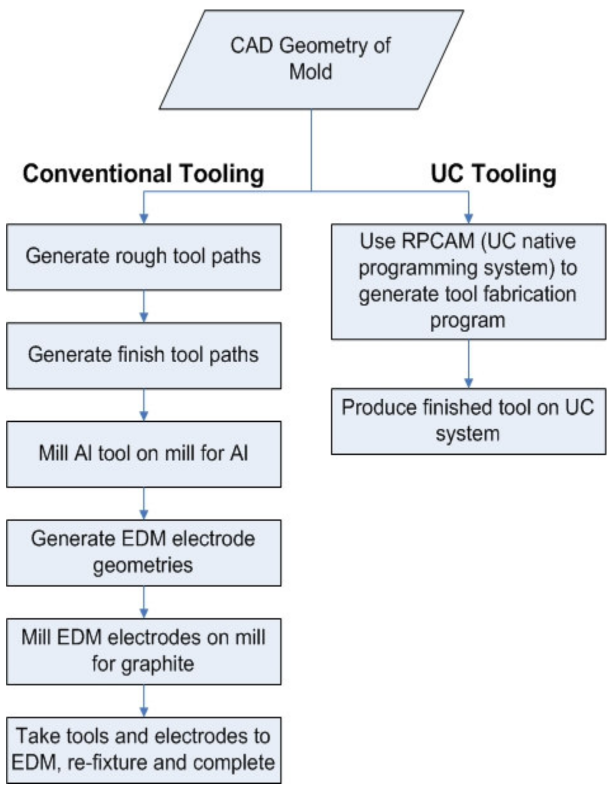


Figure 3. Conventional vs. UC process flow schematic

A third party study was conducted on time and cost savings associated with using UC to produce aluminum tooling for producing wax patterns for investment casting. In this study, the fabrication of UC tooling and waxes was compared to production of patterns using stereolithography, and production of wax patterns using conventionally fabricated tooling. The

study compared SLA patterns produced at an in house facility with quotes from two outside service bureaus, and the time/cost of producing aluminum tooling via UC with that produced by an outside tool and die shop. Figure 4 show the tools, the patterns, and the parts produced during this study.

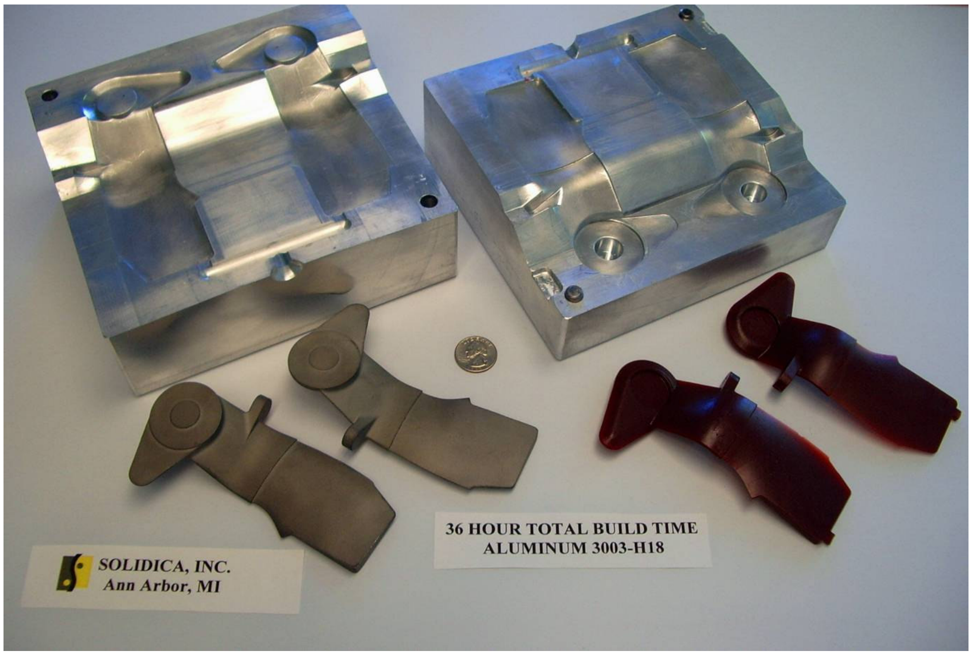


Figure 4. Investment casting pattern tooling produced via UC with wax patterns and parts.

The results showed that for volumes above 15-20 parts, it was less expensive to produce permanent aluminum tooling via UC than to produce SLA patterns. This is illustrated in Figure 5. In addition, UC tooling was found to be very competitive in timing as well, as shown in Figure 6.

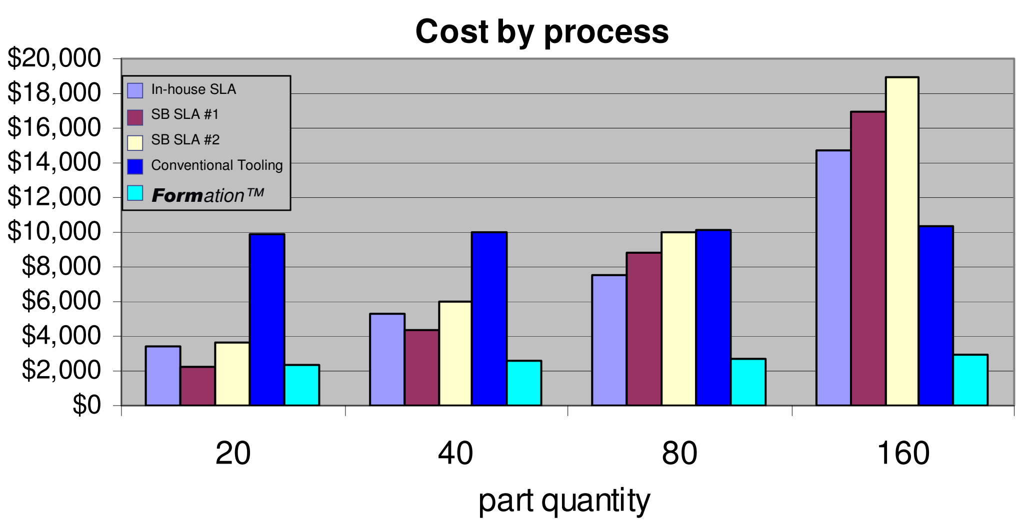


Figure 5. Cost of producing investment cast parts using various approaches

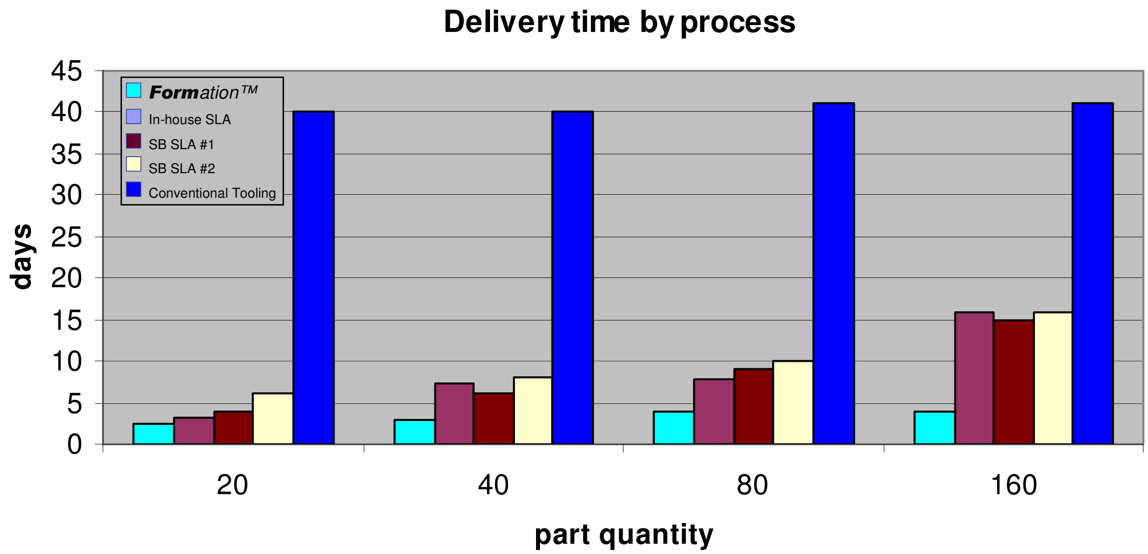


Figure 6. Cost of producing investment cast parts using various approaches

3.0 Emerging Applications

As noted above, UC is a very low temperature process in comparison to other direct metal deposition technologies such as laser and electron beam powder deposition. As a result, a number of direct manufacturing applications are possible with this process. Some of these include:

- Continuous Fiber Reinforced Metal Matrix Composites (CFR MMCs)
- Functionally gradient and dissimilar metals laminates for various applications
- Embedded sensors and electronics
- Embedded fibers with non-structural capabilities

These capabilities have applications as diverse as

1. Real time control of mold temperatures
2. Advanced structural materials
3. Rugged wireless sensors
4. Tamperproof enclosures for electronic devices

3.1 Composite Materials and Laminates via UC

As shown in Table 1 above, ultrasonic metal welding allows many materials that are metallurgically compatible during liquid phase welding to be successfully joined. In UC, this characteristic is exploited to allow unique functionally gradient materials to be fabricated. Some examples include:

- Metal-metal laminates
- Continuously reinforced metal matrix composites
- Embedded structural ceramic reinforcements

Metal laminates including Al-Cu, Al-Ti, Ni-Ti, and other multi-layer couples have been produced. Figures 6 showing Al-Ti provide a good example system, as it is relatively difficult to produce such laminates using most techniques [2].

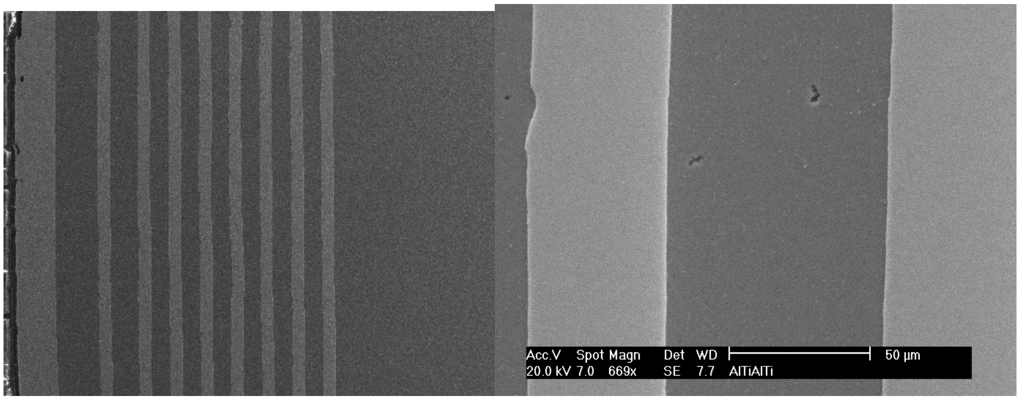


Figure 6. Ti Al laminate produced via UC at lower and higher magnification.

Similarly, meshes can be embedded between two layers of material to increase stiffness with a relatively small increase in weight, as illustrated in Figure 7, where a stainless steel mesh is embedded in a 6061 Al matrix.

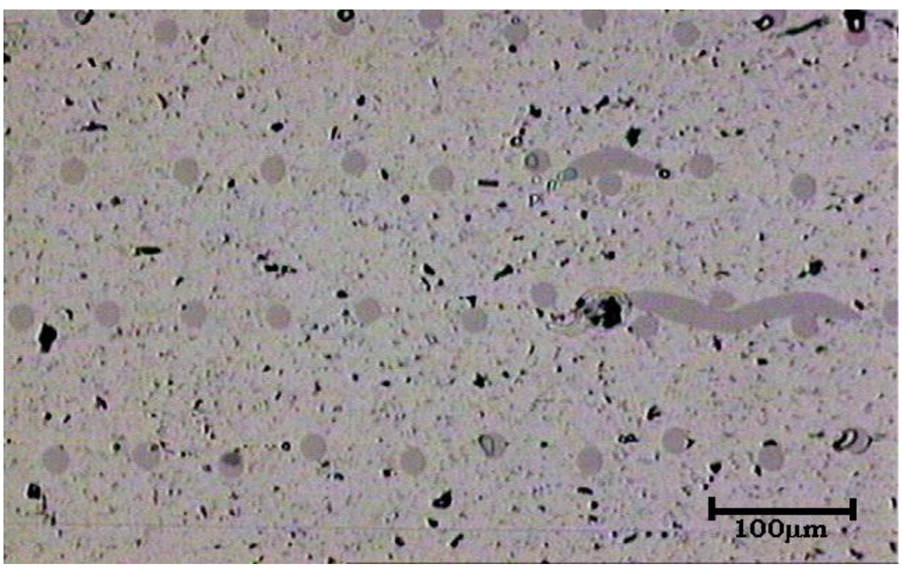


Figure 7. 316 stainless mess embedded in 6061 Al matrix via UC.

Although detailed studies have not been conducted, there is no evidence that a reaction occurs between them metal matrix and the embedded fiber, or the laminate layers, even for material couples such as Al-Ti in which such reactions are known to occur. Figure 8 below shows an example of SiC fibers embedded in an aluminum matrix in which this was investigated. As illustrated in Figures 8 a,b, and c below, use of EDS to map the distribution of key elements Si, and Al following UC to embed an SiC fiber in Al, failed to show any evidence that diffusion or reactions occurred at the interace between the Al matrix and the fiber during the embedding process.

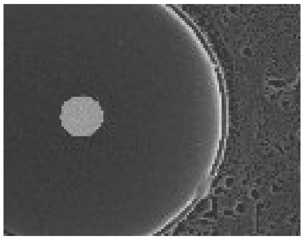


Fig. 8a. SiC fiber in Al

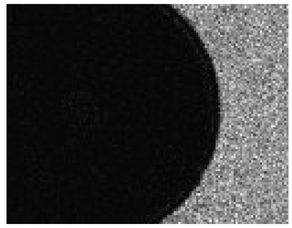


Fig. 8b. Al elemental map.

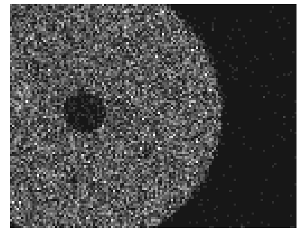


Fig. 8c. Si elemental map

In addition to relatively robust materials such as metal sheets or structural fibers, delicate and thermally sensitive materials have been embedded in aluminium matrices via UC. Figure 9 shows 50µm optical fiber embedded in a 3003 T-0 aluminum matrix, by placing it between 150 µm foil layers prior to ultrasonic consolidation. Figure 10 shows that the fibers can be illuminated following the consolidation process.

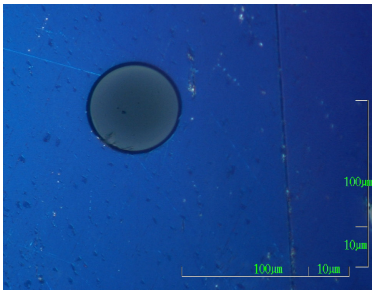


Figure 9. Optical fiber embedded in Al via UC.

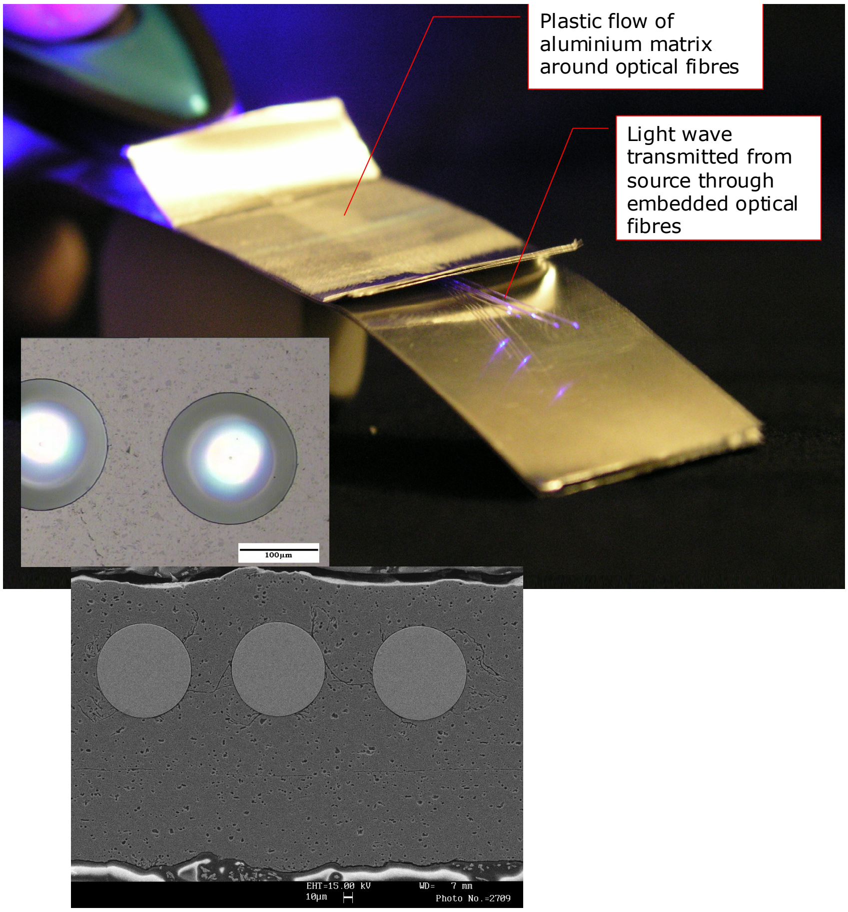


Figure 10. Illuminated optical fibers following ultrasonic consolidation in Al.

Figure 11. SMA fibers embedded in Al matrix (10X).

Similarly, SMA fibers can be embedded in an aluminium matrix (figure 11), and because of the low temperature at the interface during consolidation (approximately 175C) and the very brief duration (approximately 100 msec) of the temperature excursion, their properties are unaffected, as shown in Figure 12, below.

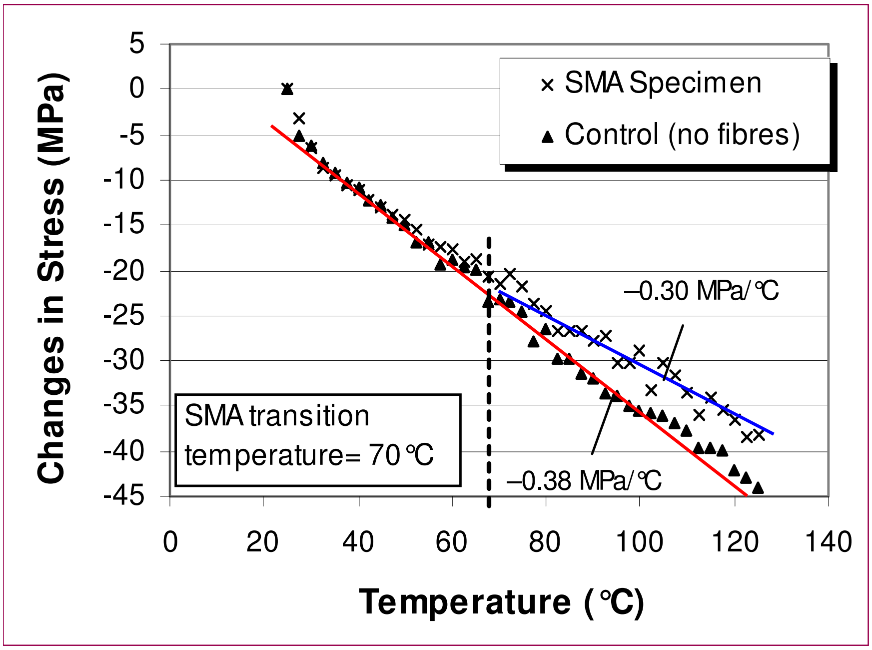


Fig.12 Macroscopic thermal mechanical responses of 5% volume fraction SMA fibre embedded aluminium alloy

In addition, complete electronic devices can be embedded in aluminium, while retaining their functionality. Recently RFID, wireless transmitters, and sensors of various types have been encapsulated in UC enclosures. Although metal-to-device contact is unachievable, unlike the metal-fiber contact illustrated above, the capability to produce materials, components and assemblies with unique capabilities has been demonstrated. Some applications include structural health monitoring, tamperproof enclosures for sensitive applications, autonomic structures and sensor networks, and many others. These emerging capabilities provide interesting new directions for research in Ultrasonic Consolidation.

4.0 Conclusion

Ultrasonic Consolidation is a direct metal manufacturing technology with initial applications in rapid tooling and rapid prototyping. Recent developments in the field show that it has promise for advanced structural materials such as MMCs, and in autonomic devices and components for a range of applications. However, more data on the mechanical and physical properties of the materials produced using this technology are required.

MEETING DISCUSSION – PAPER NO: 21

Author: D. White

Discusser: L. Pambaguian

Question: How easy is it to procure the tape you use? Do you have specific requirements with respect to the procurement?

Response: Feedstock can be procured from foil re-rollers on a convenient basis. Certain dimensional accuracy and surface condition requirements must be met.

Discusser: P. Brown

Question: Can your technique be used to bond metal/composite materials and steels?

Response: I think it is possible - preliminary observations with polymer based composites would indicate that this is the case, but no detailed experiments have been performed.

Discusser: D. Dicus

Question: How are Al tooling applications impacted by the poor transverse bonding in your laminates?

Response: Tooling is generally bonded in compression + shear. Tests of our molds using glass filled polymers have failed to produce shear failures in the molds.

Discusser: J. Savoie

Question: 1. Have you performed shear tests? 2. In case use of annealed sheet, the bounded zone experienced plastic deformation while the core is un-deformed. After final annealing, what would be the grain size distribution?

Response: 1. Shear tests have been performed in a long transverse testing where results are dominated by tape geometry and incomplete tape-tape welds in “Z” axis. No sheet shear tests have been performed. 2. I have not performed such a test and don’t know what effect might be.

SOLIDICA

Ultrasonic Consolidation: Status Report on Development of Solid State Net Shape Processing for Direct Manufacturing

May 15, 2006

Dawn White, Solidica

Outline

- Solidica corporate background
- Ultrasonic Consolidation Process
  - Bond Formation Mechanisms
  - Defects
  - Surface Contact Analysis
  - Friction Theory
  - Experiment
- Status
  - Material Properties
  - Commercial Applications
- New Development and Applications
- Summary

SOLIDICA

- Founded Jan 1999 by Dr. Dawn White
- Ann Arbor, Michigan Based
- Engineering-based company

Mission

Expand the frontiers of our customers product development through additive manufacturing

Solidica Key Partners and Customers

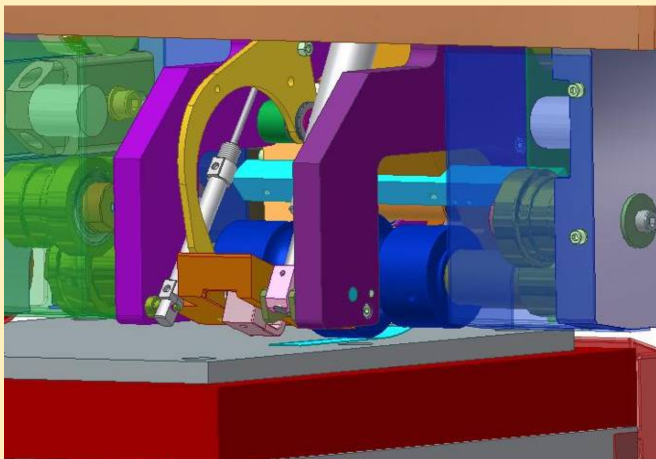
- Rapid Tooling
- Engineered materials
- Electronics packaging
- Embedded sensors
- Metal Matrix Composites
- Rapid part repair
- Tamperproof devices

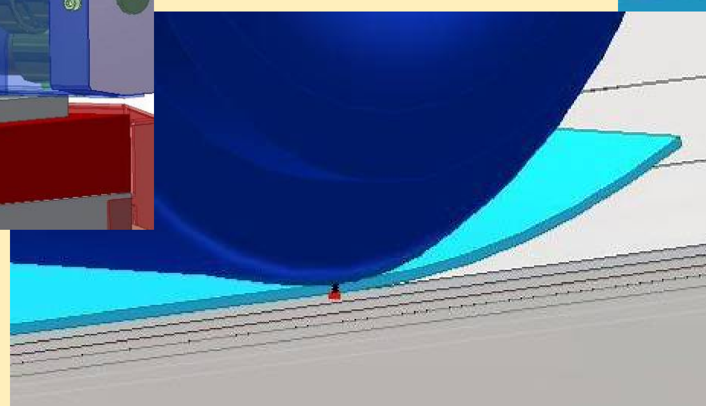
What is Ultrasonic Consolidation?

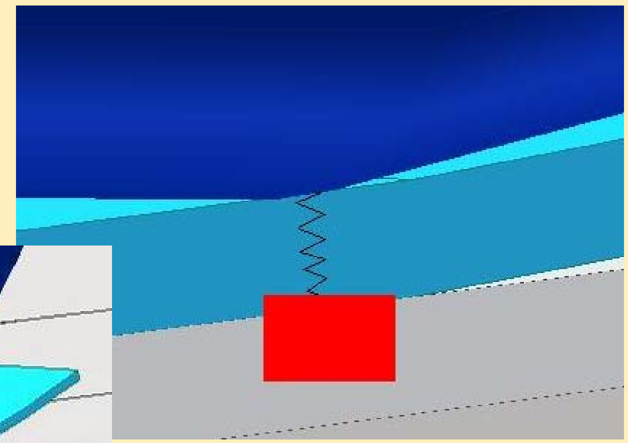
- A solid state, layered additive manufacturing process that employs ultrasonic energy to produce bonds between metal layers
- Solidica has implemented this in a system analogous to “metal tape layup”
- Solid state joining provides significant benefits in additive manufacturing
  - Low temperature (~0.5Tm), and energy consumption (~10% of melting processes)
  - Majority of material unaffected by process – metastable microstructures can be retained
  - Fast 250-500 cm3/hr deposit rate
  - Low residual stresses
  - Atmosphere control requirements minimized

What is Ultrasonic Consolidation?

Ultrasonic energy is used to create a solid-state bond between two pieces of metal



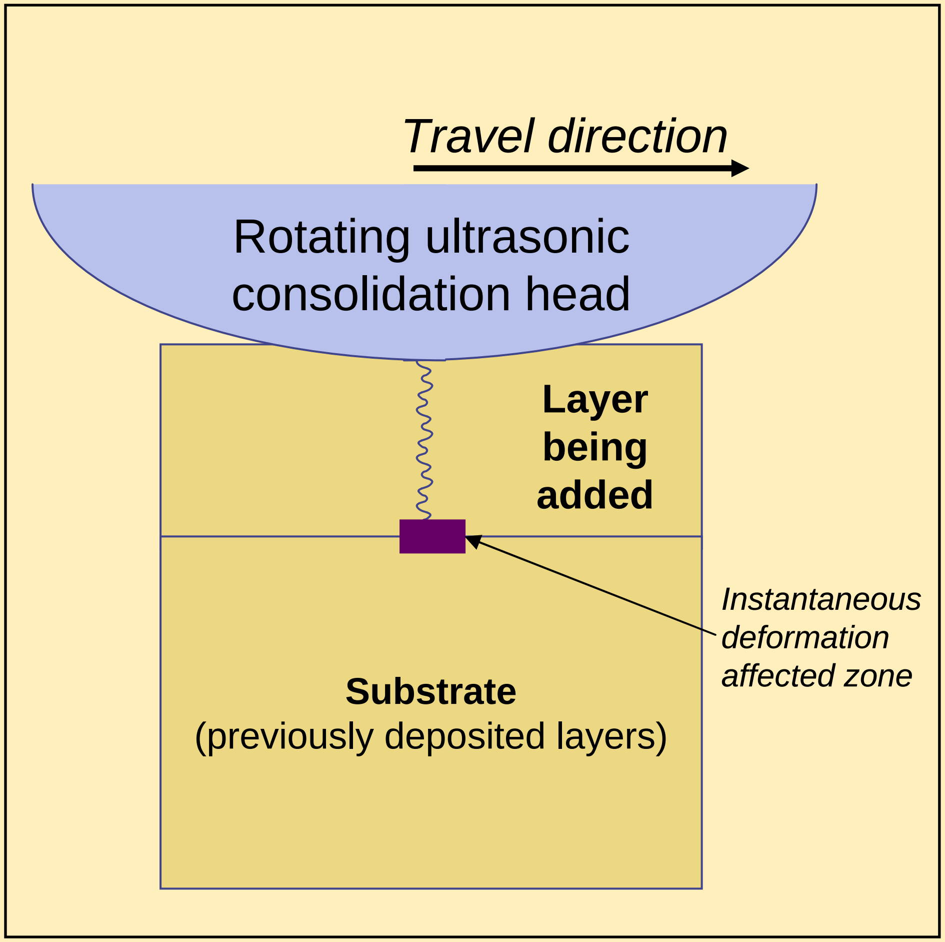




True metallurgical bond
8 layers Al, 100x

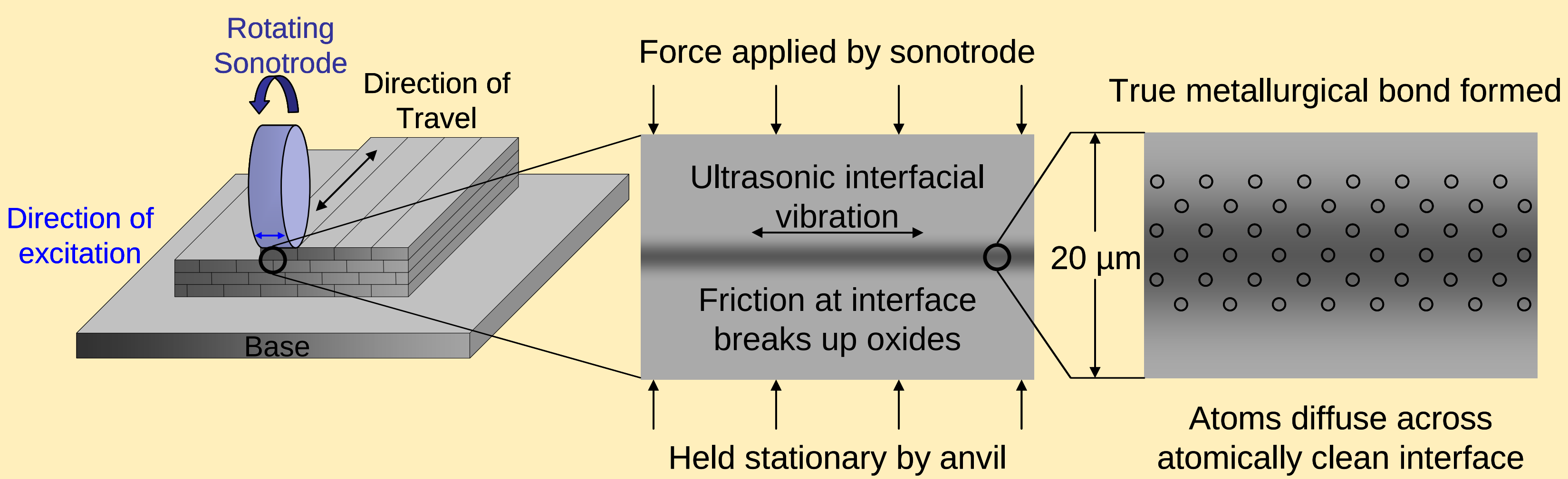
Temperature Changes

- In ultrasonic joining, peak temperatures rarely exceed 0.5Tm
- Very small affected volume
- Substrate material largely unaffected



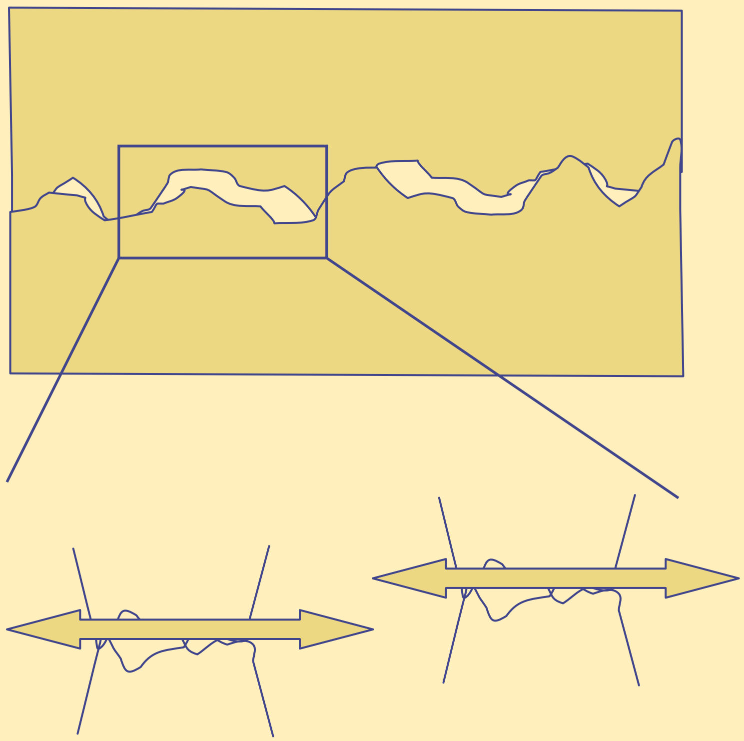
Fundamentals of Ultrasonic Consolidation

- Based on ultrasonic metal seam welding
- Combines continuous rotating contact during ultrasonic welding with metal tape layup approach



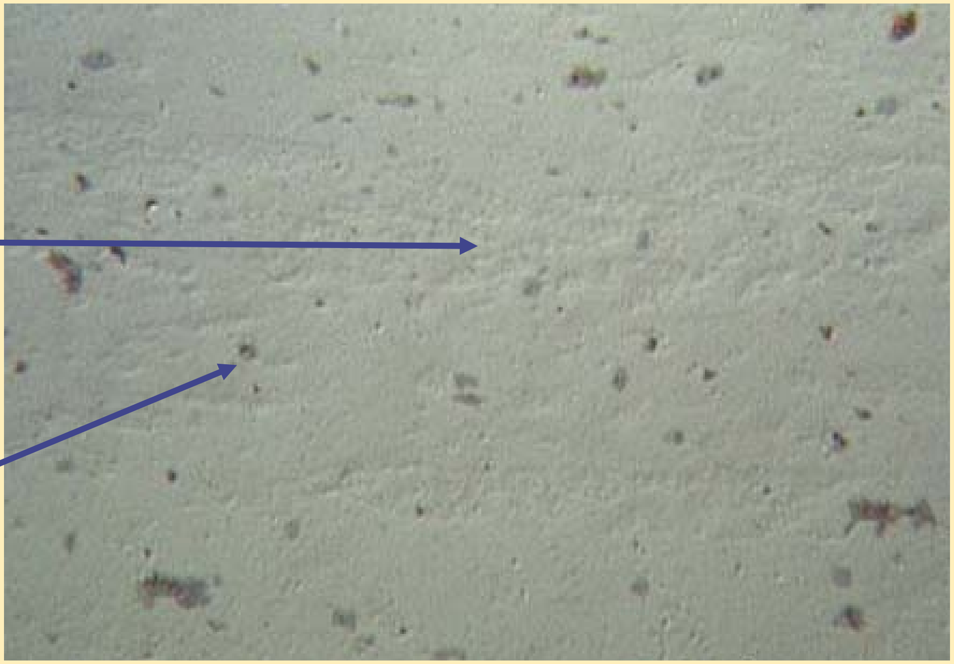
Mechanisms

- Initial clamp force collapses asperities
- Ultrasonic energy is coupled through the stack into the anvil
- The interface experiences simultaneous fracture of the oxide films
- Parent material welds across the interface
  - –Grains reorient to lower energy positions, low angle tilts, and dislocation annihilation
- Weld zone grows to maximum area
- Weld zone becomes damaged - continued sonication destroys weld quality



Microstructure

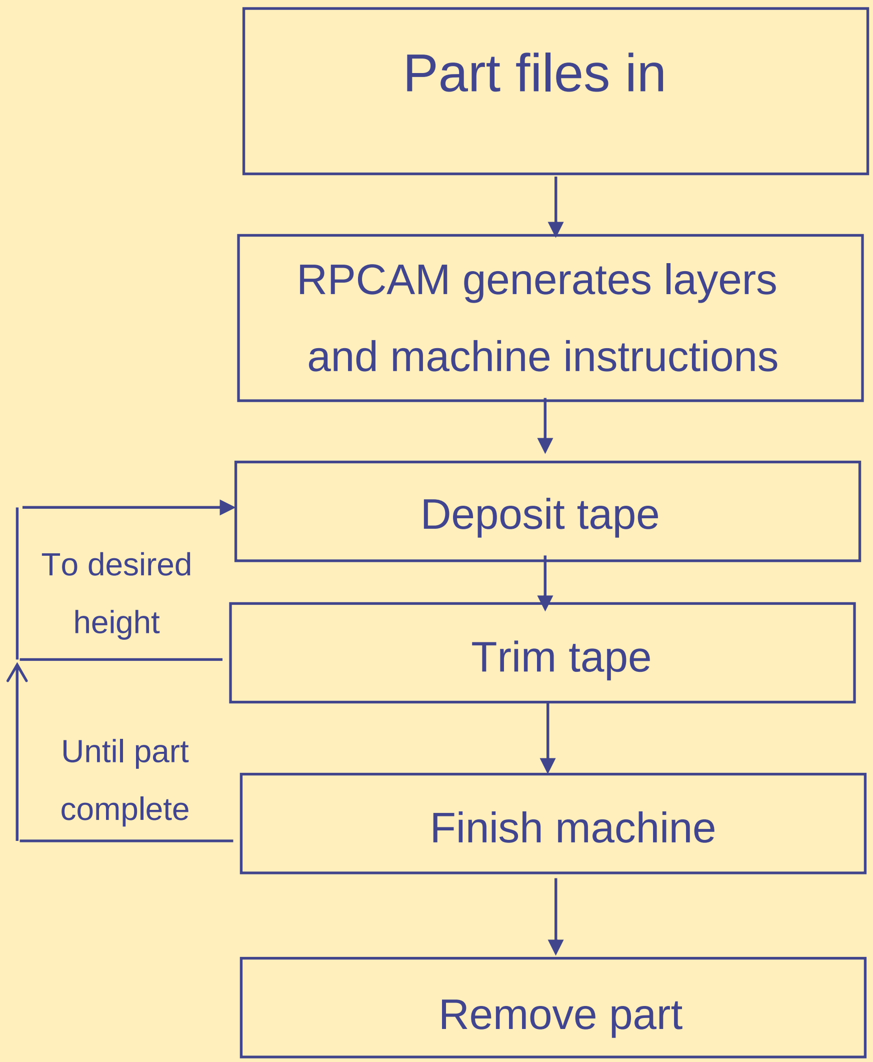
- Bond region ~ 5- 20 μ
- Plastic flow occurs in this "deformation affected zone" (DAZ)
  - Inclusion refinement
- Featureless, micron or nano-structured bond region



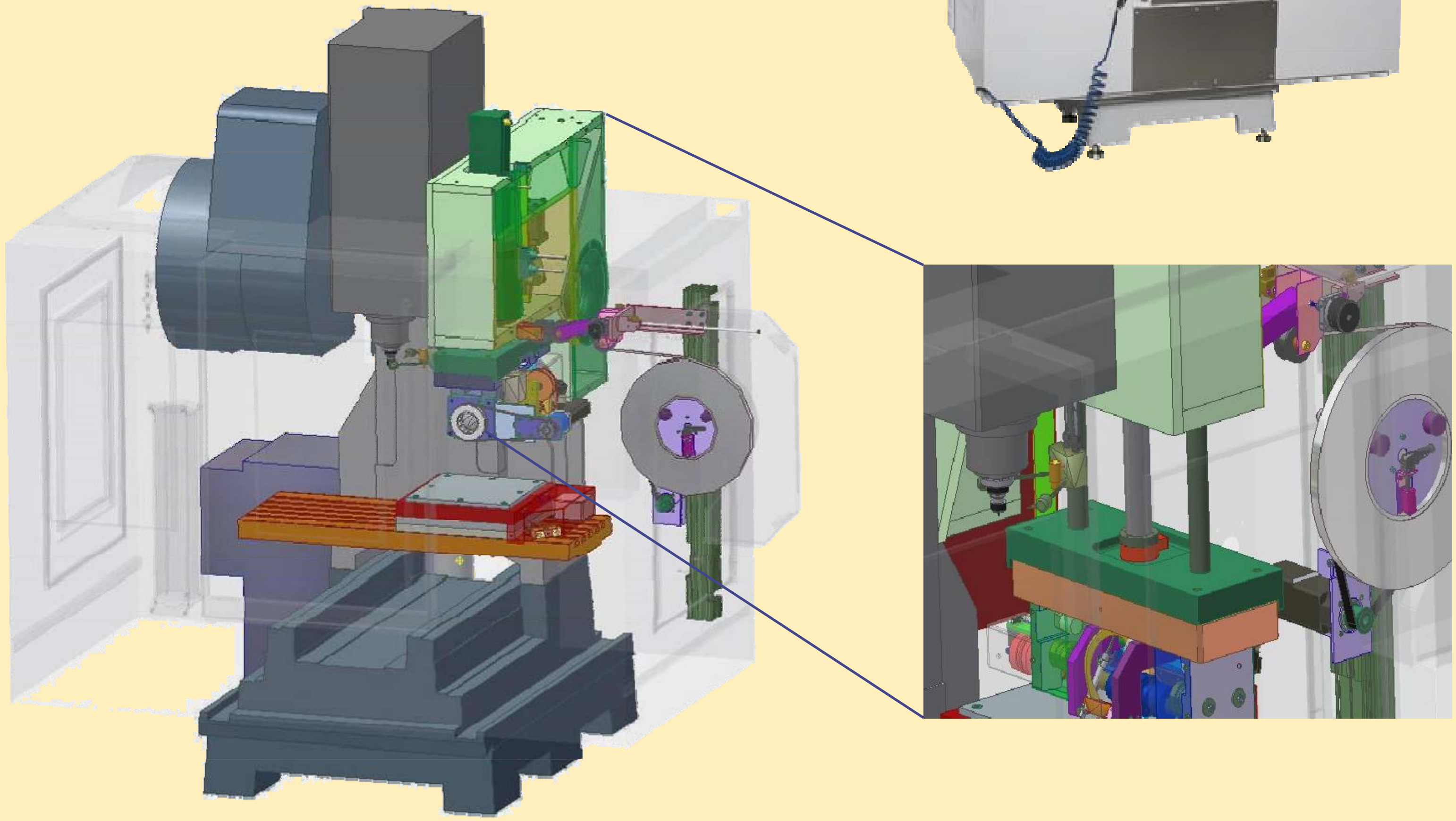
1000x optical

Ultrasonic Consolidation Operating Sequence

- RpCAM™, Windows™ based software for layer-by-layer part-build on Solidica *Formation*™ machines.
- 3D IGES CAD model input
- Tool paths generated by PowerMILL™ from Delcam
  - Default tool paths for easy operation
  - Interleaves additive and subtractive functions
  - Incorporates key UC process parameters for all joining cases
  - Provides for support material application
  - Accounts for varying and multiple build materials
  - Generates specialized volumes for machining



Formation™ Machine



Advanced Proprietary Software Engine

- RpCAM™, Windows™ based software for layer-by-layer part-build on Solidica *Formation*™ machines.
- 3D IGES CAD model input
- Tool paths generated by PowerMILL™ from Delcam
  - Default tool paths for easy operation
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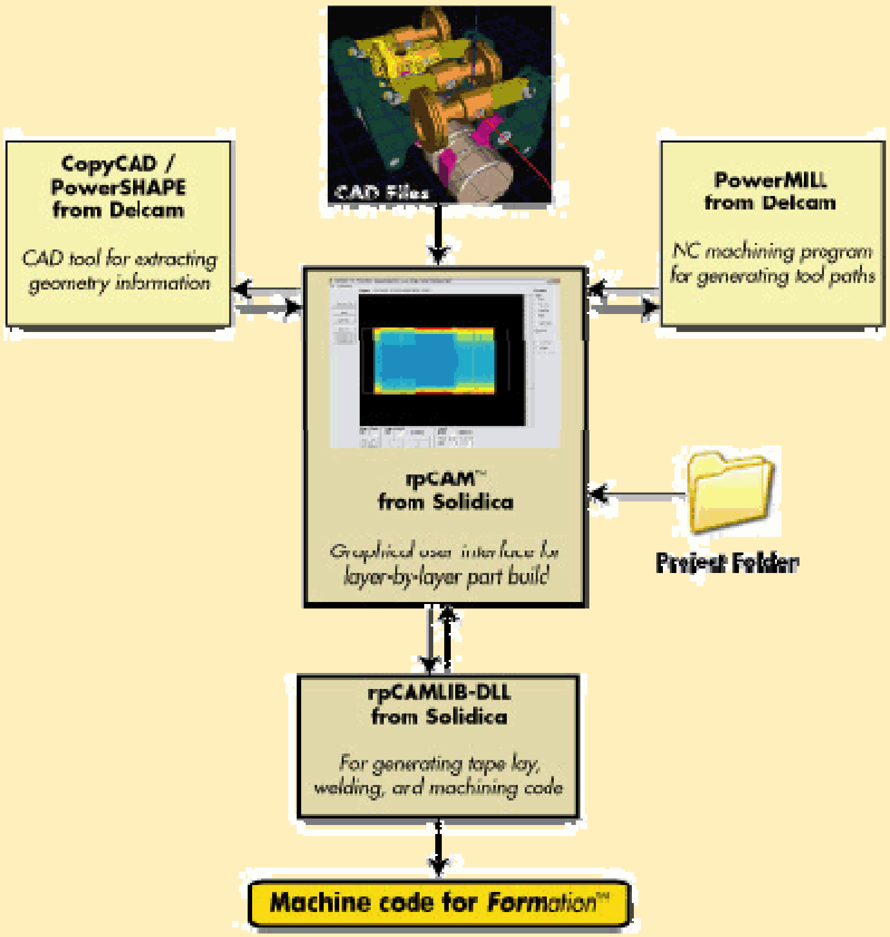
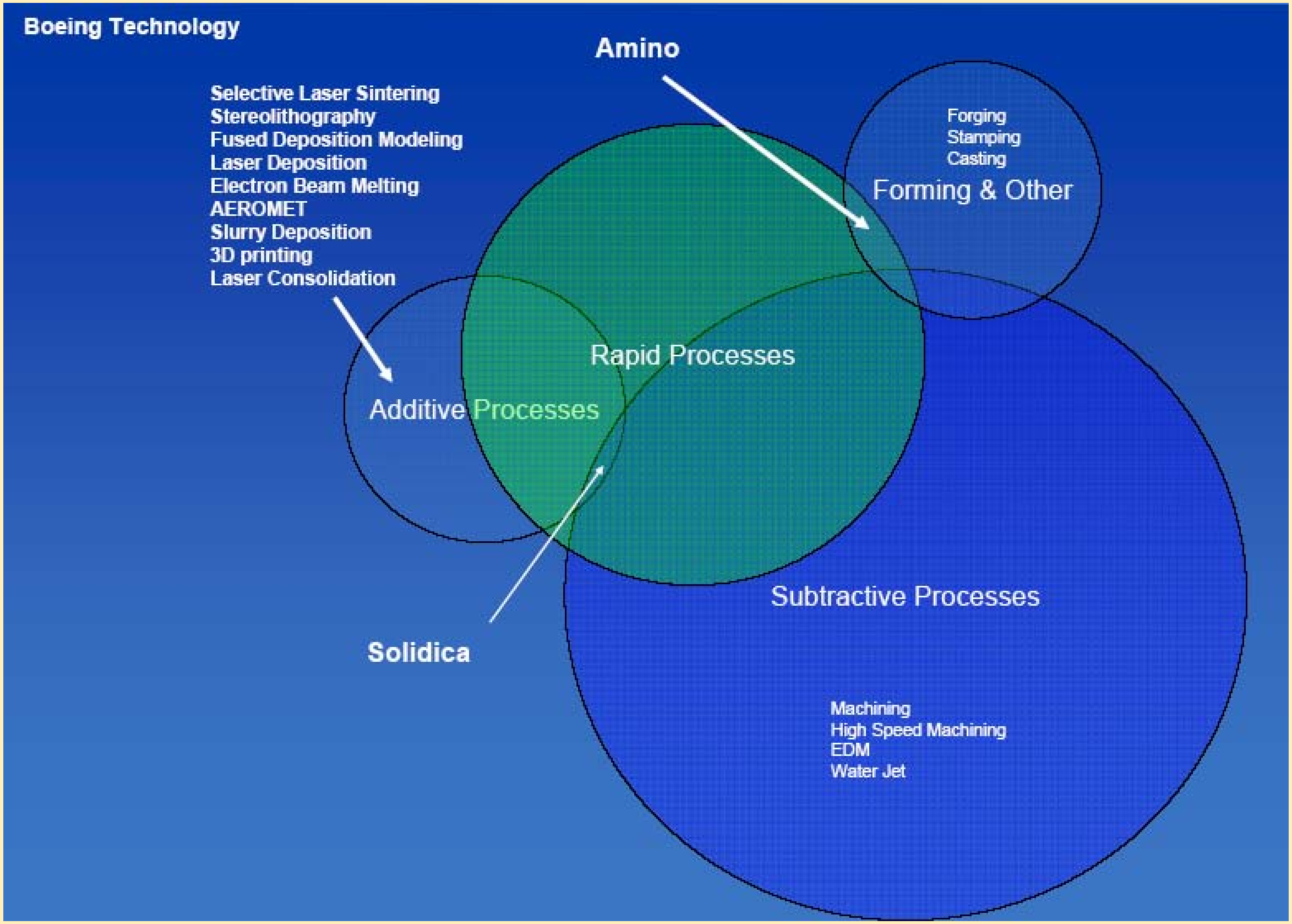
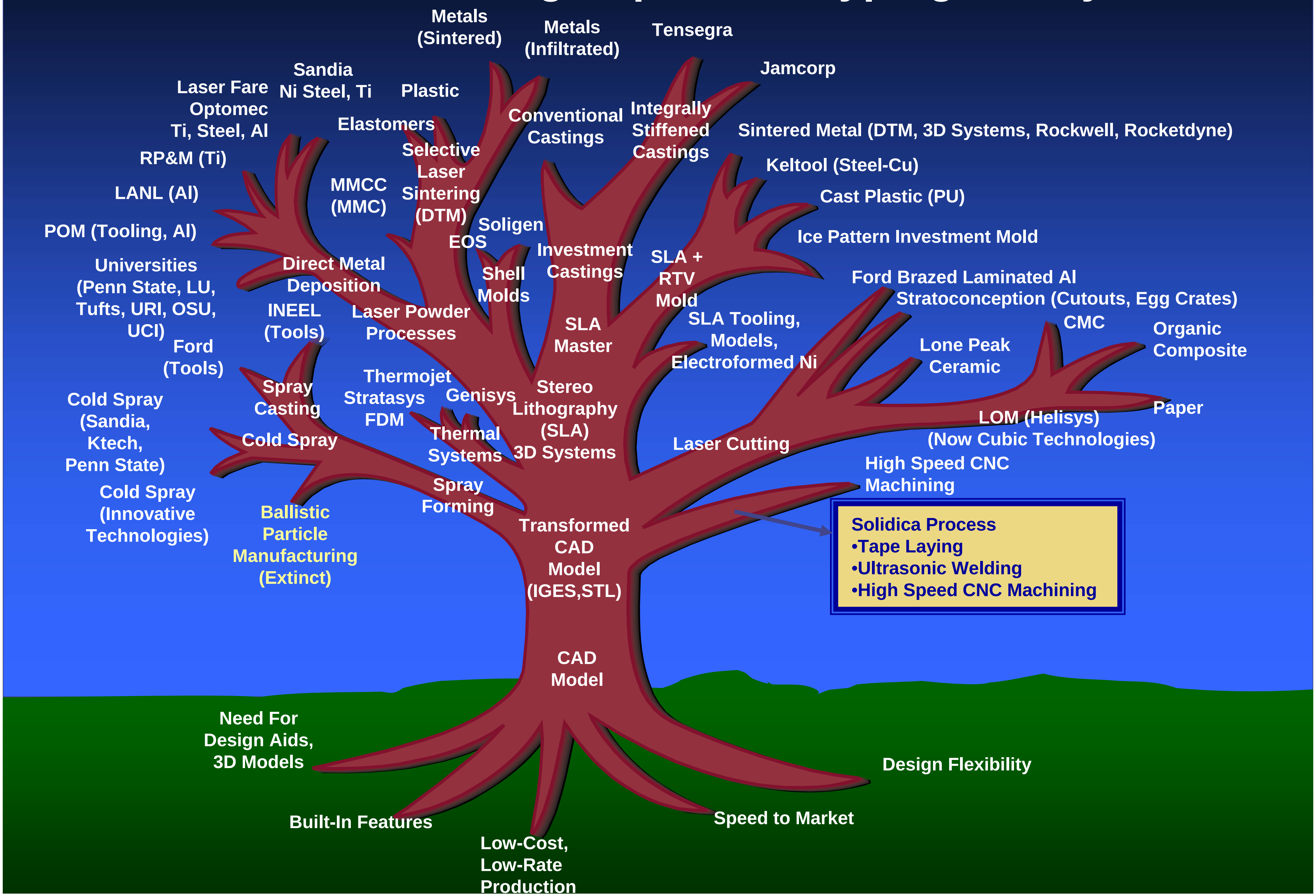


Typical Technology Characterization



Source: Blake Slaughter, 2005 DMC Presentation

Direct Manufacturing/Rapid Prototyping Family Tree



Formation™ Machine Options

- *Formation™ CT*
  - *Base tooling and metal prototype platform*
  - *400 x 400 x 250*
  - *Target market: rapid tooling in Al*

- *Formation™ XT*
  - *Larger footprint research and development platform -*
  - *1125 x 750 x 300*

Tooling

Conventional aluminum wax tooling

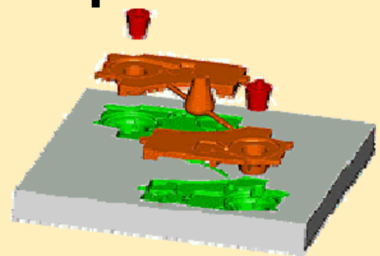
Process…

1. Prepare CAD file of tool
2. Write CNC Machining Program
    a. Rough cut
    b. Finish cut
3. Write programs for EDM electrodes
4. Program EDM machine

1. Do CNC milling
    a. Rough cut
    b. Finish cut
    c. Machine electrodes

Do EDMing

Requirements



One mill for metal, another for graphite

EDM for deep narrow features

Aluminum wax tooling with Formation™

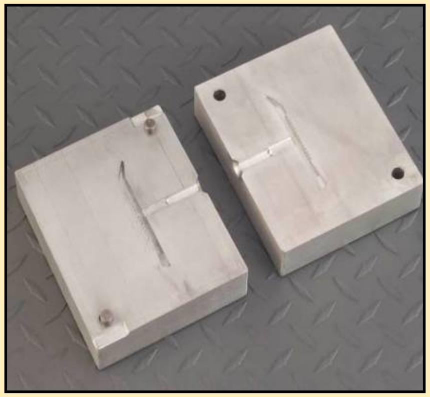
Process…

- One machine
- One program
- One operator
- One piece flow

36 hour build time for 2 piece die set with total volume of 200x175x100 mm

UAM Tooling Benefits

- Most accurate rapid tooling technology available
- Tools in 2-4 days – Ping half mold ~45 hours total (processing and build)
- 50%+ cost savings (labor, material, energy)
- Replaces multiple machine tools and EDM centers – “One machine” machine shop
- Builds can be stopped - Implement engineering changes
- Use existing RP expertise to bring tooling in-house - Technicians can easily learn Solidica’s system
- Ability to embed process monitors (temperature, pressure, etc.)
- Ability to create conformal cooling for increased cycle time

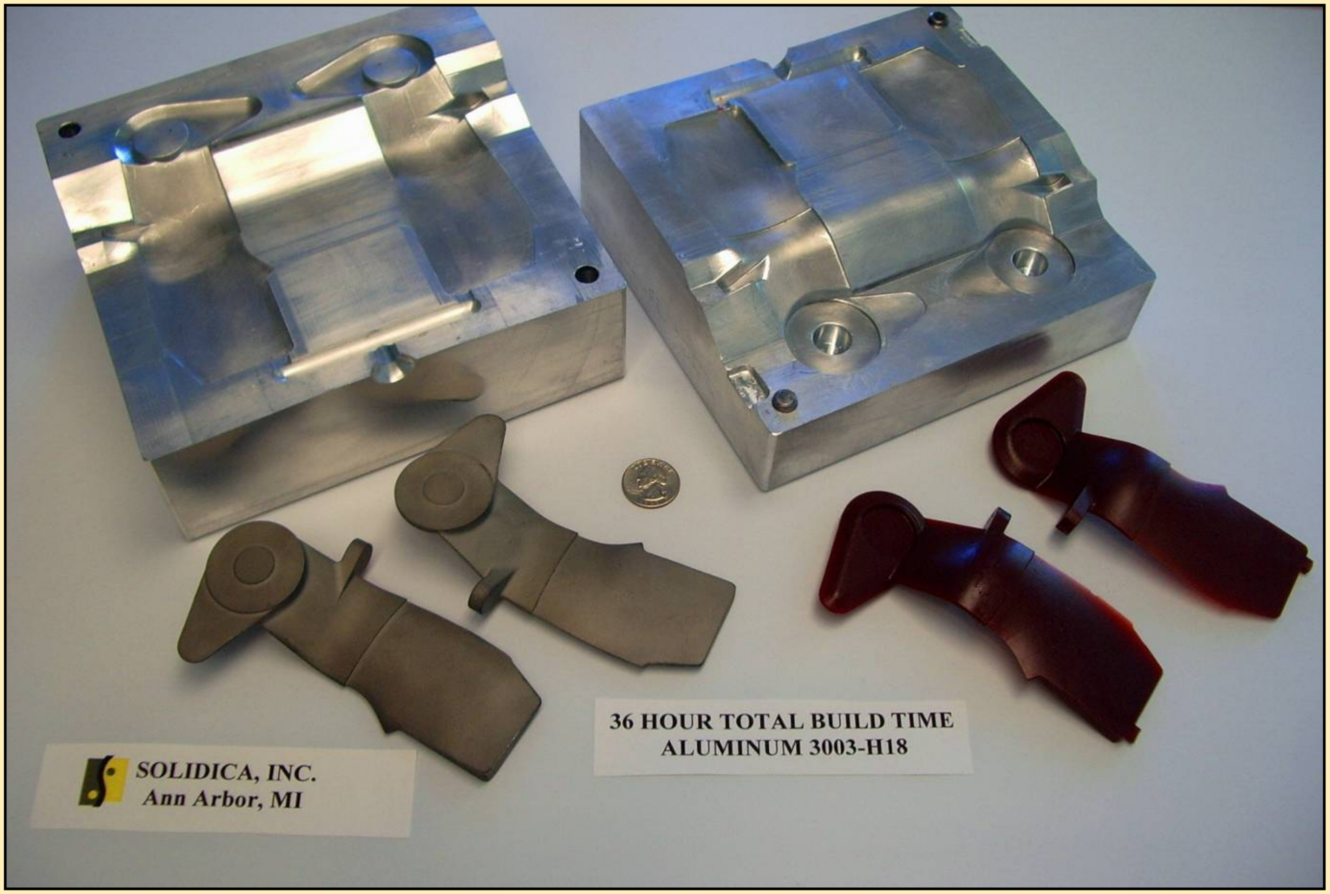


Conformal Cooling for Injection Molding

- Fully engineered thermal management
- Increased injection molding cycle times
- Heating and cooling lines can be integrated for multistage injection

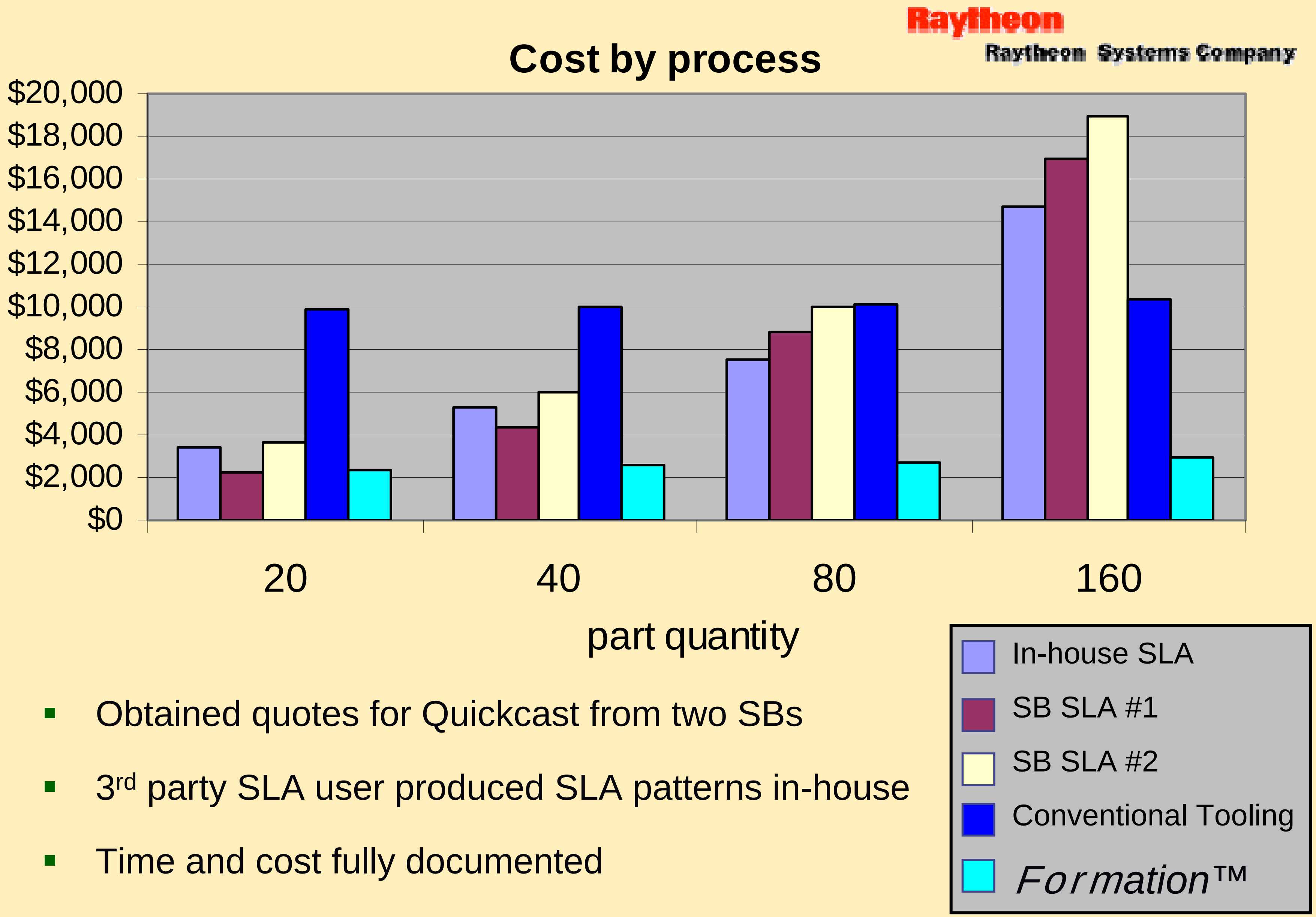
Investment Casting Example

Raytheon
Raytheon Systems Company



Solidica cooperated with Raytheon Systems to produce these tools, waxes, and parts as a case study.

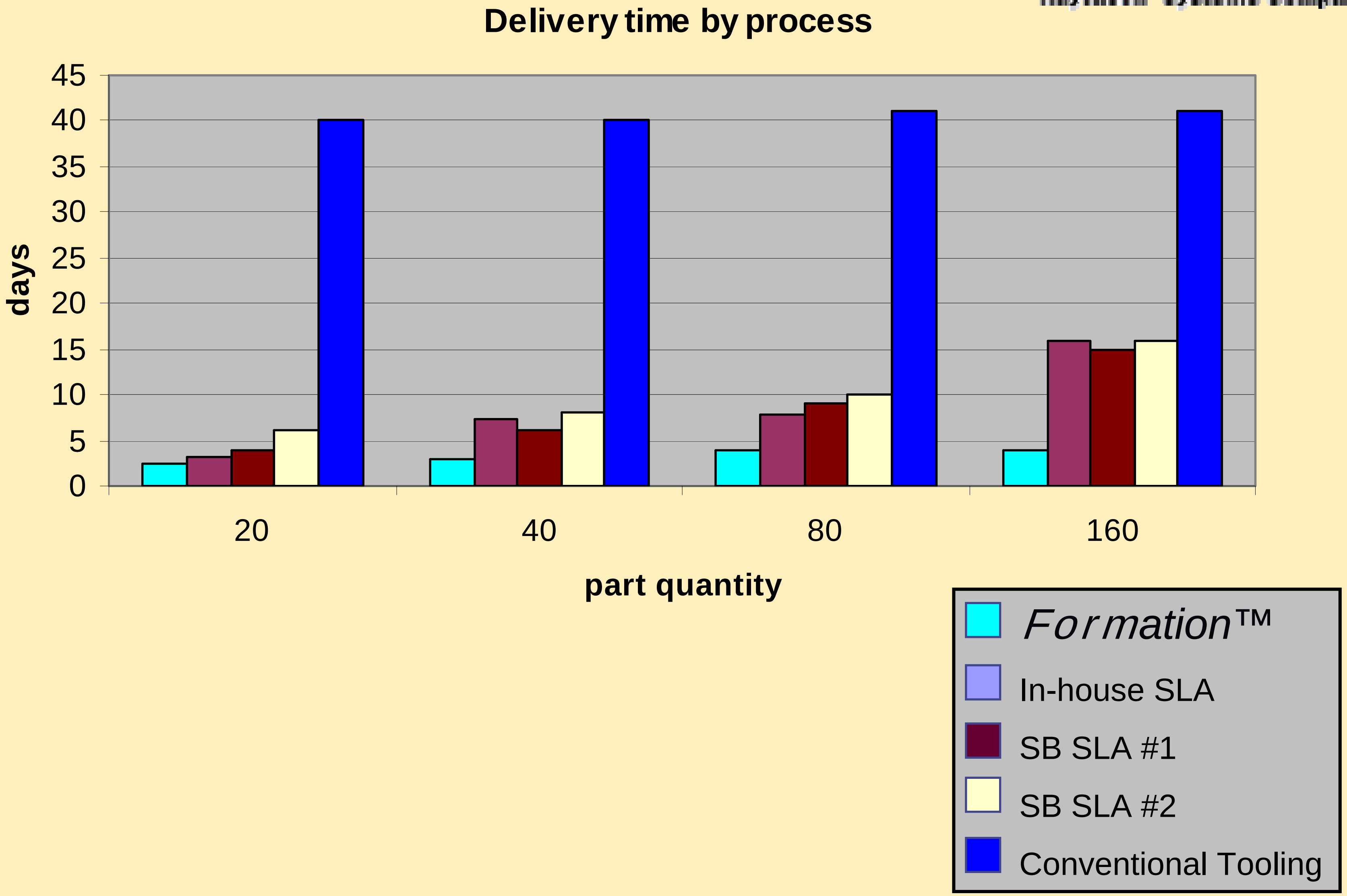
Putting it to the test – cost comparison



- Obtained quotes for Quickcast from two SBs
- 3rd party SLA user produced SLA patterns in-house
- Time and cost fully documented

Putting it to the test – time comparison

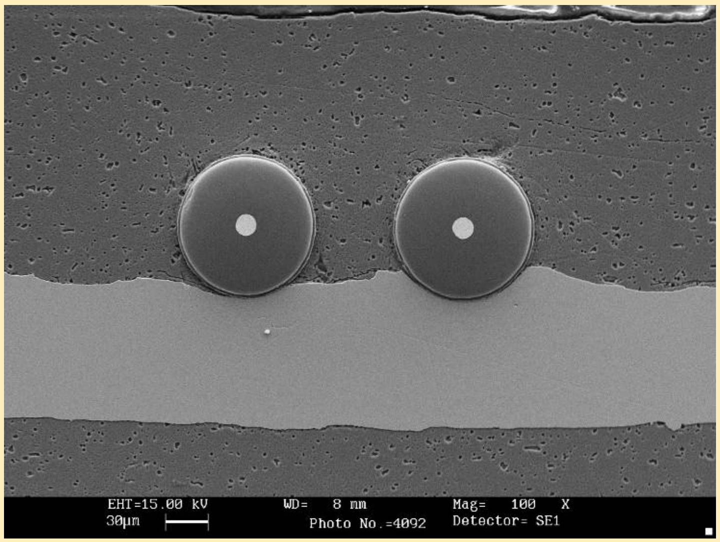
Raytheon
Raytheon Systems Company



Properties

Materials for Ultrasonic Welding

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al Alloys	■	●	■	●	●	■	●	●	■	●	●	●	●	●	●	■	●	●
Be Alloys		●	●			●										●		
Cu Alloys			■		●	●	●	●	●	●	●		■	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe Alloys						■			●	●	●		●	●		●	●	●
Mg Alloys							●						●			●		
Mo alloys								●	●		●			●		●	●	●
Ni Alloys									●	●	●			●		■	●	
Pd										●			●	●				
Pt Alloys											●	●		●		●	●	
Si													●	●				
Ag Alloys													●	●				●
Ta Alloys														●		●	●	
Sn															●			
Ti Alloys																■	●	
W Alloys																	●	
Zr Alloys																		●



■ Demonstrated UC pairs

● Demonstrated USMW pairs per AWS

Al

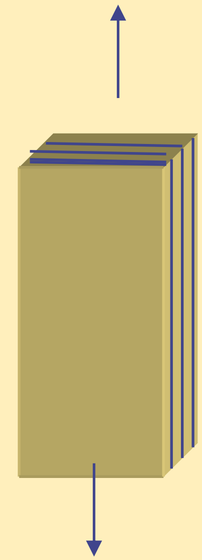
1100, 3003, 3005, 5054, 6061

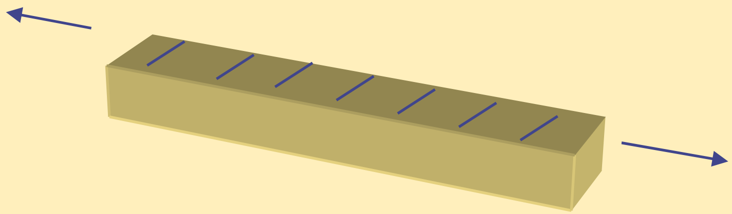
Mechanical Testing

- Tensile 3003 H18
  - Longitudinal
  - Long transverse
- Charpy Impact H-18
- Ballistic Impact/spall strength 1100 T0, Al-CPTi

Tensile Testing

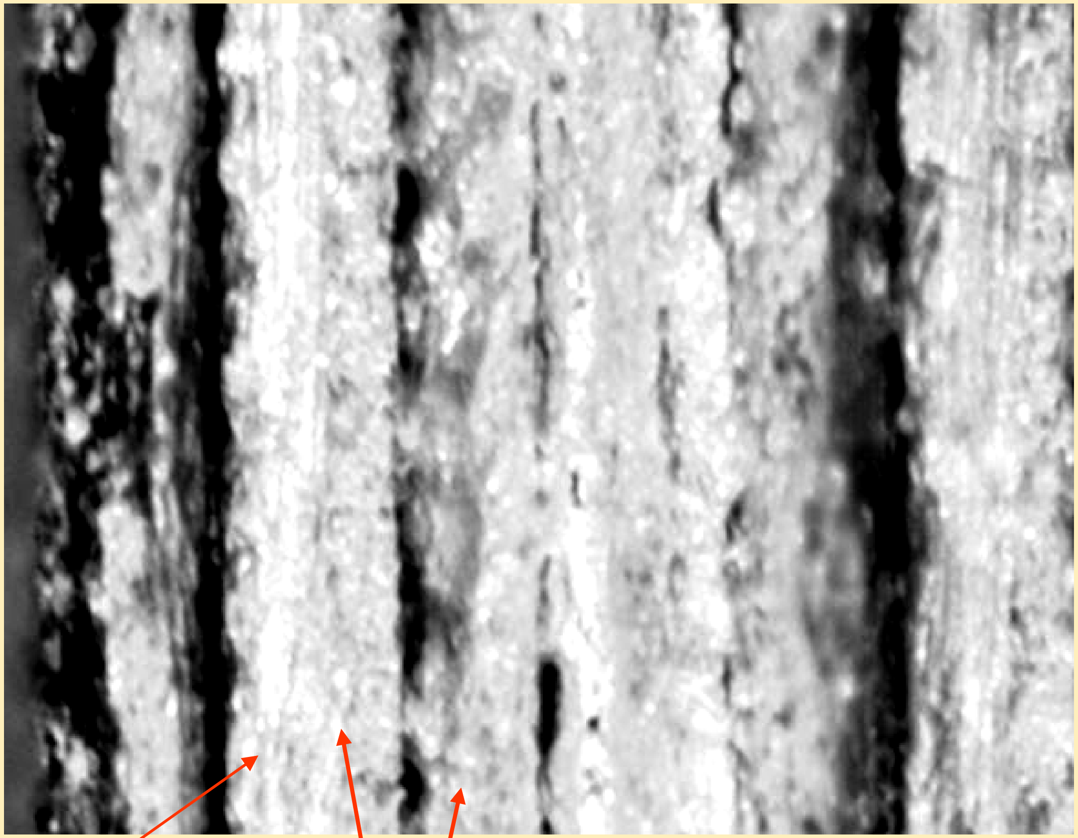
- Longitudinal
  - 3003 H18 AR 27 ksi YS, 29 ksi UTS 34.6 ksi (120%), 4.5% elongation
- Long Transverse
  - 3003 H18
  - UTS   20.2ksi (70.5%)





Tape layup build style contributes to lower long transverse values

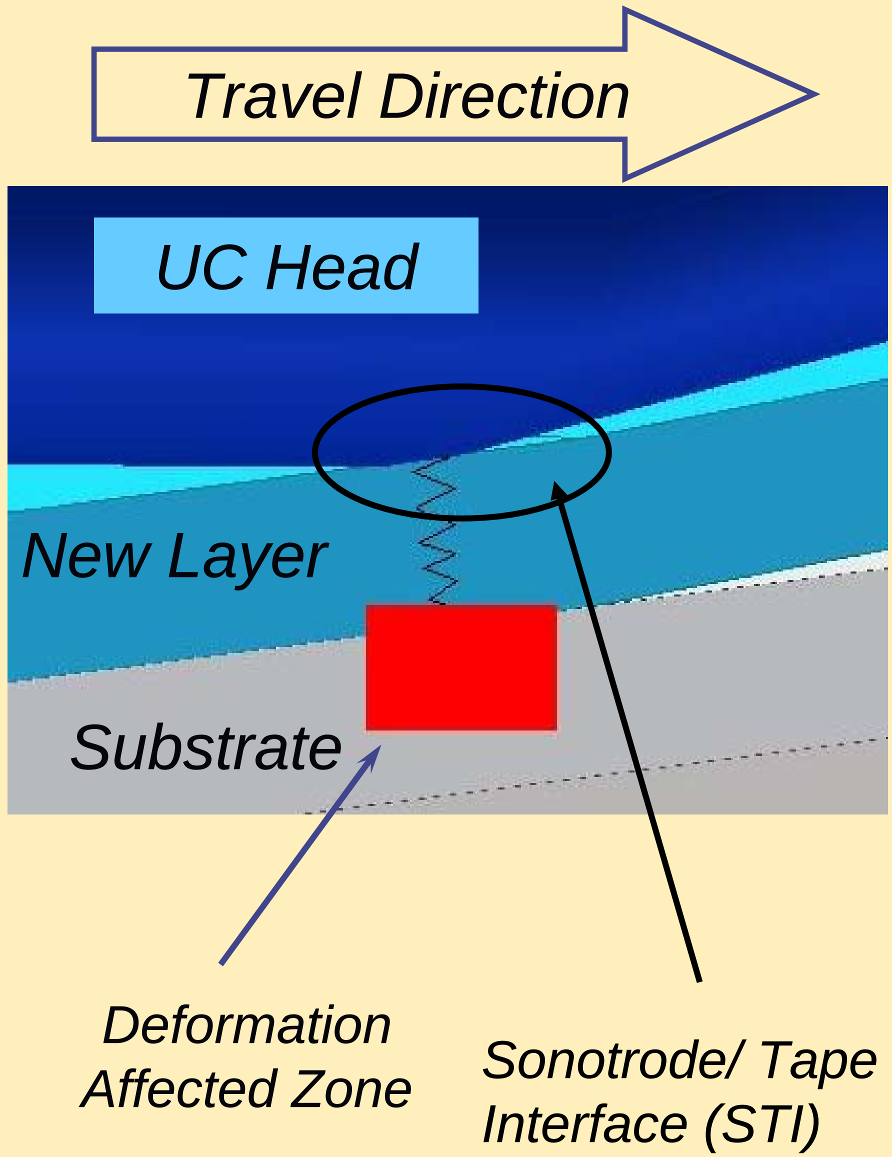
- Tape intersections are not fully welded, and result in lower effective section thickness, and reduced strength/elongation



As slit surface

Ductile failure

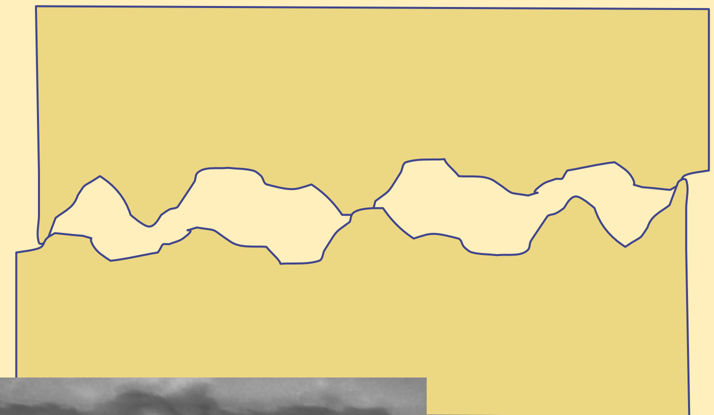
Origin of Defects

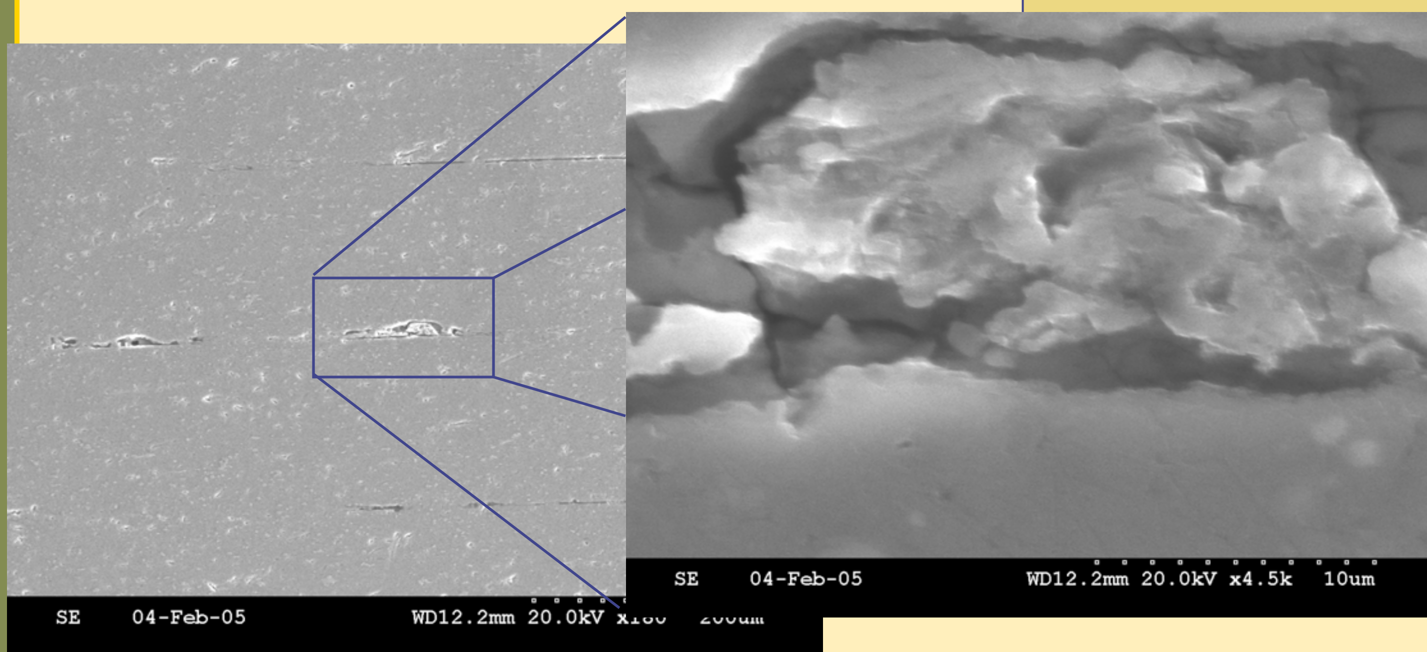


- Transfer ultrasonic energy from horn to DAZ without losses
- Horn is textured to grip the tape, transfers texture to tape surface

Wear and Asperity Contacts

•Variation in surface morphology -> incomplete contact + formation of wear debris





Engineering Parameters

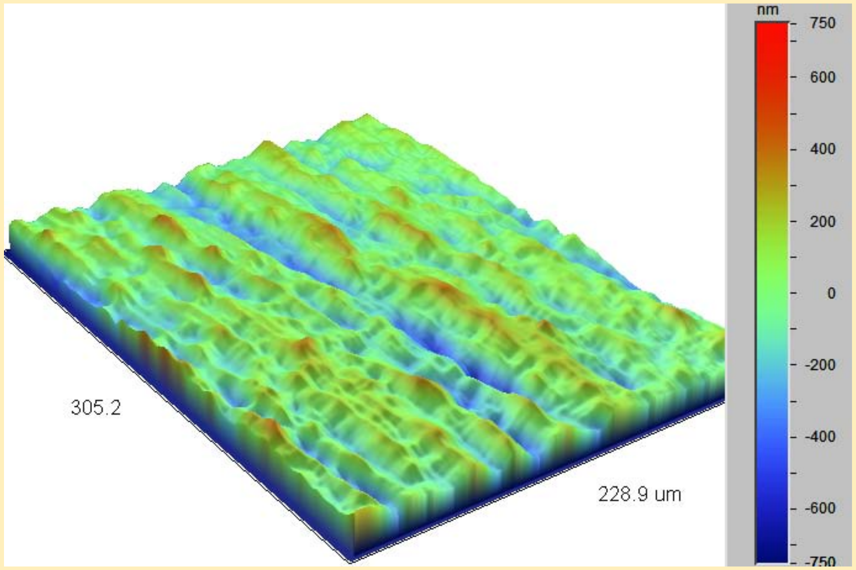
Goal: 100% Consolidation

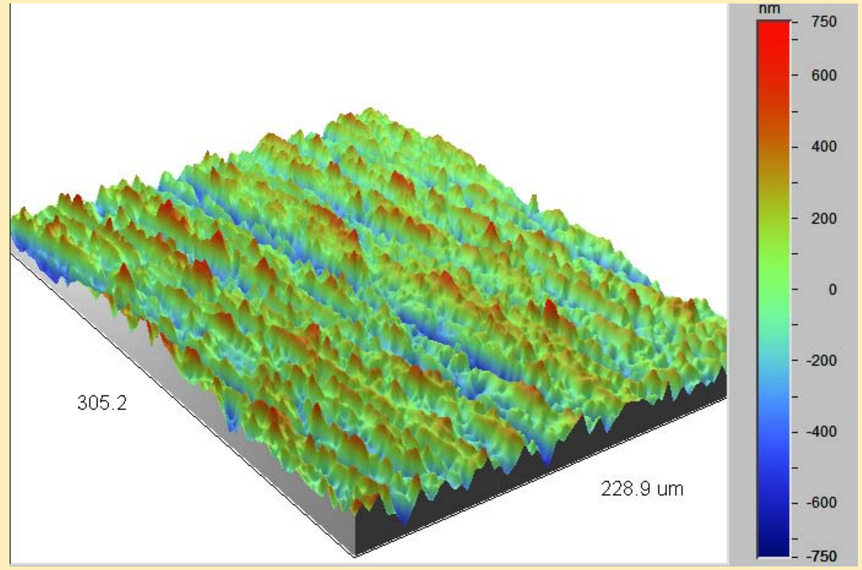
- Load (pressure), W
- Amplitude, A
- Speed (time or number of cycles), t
- Frequency, f
- Energy

$E = \mu AWft$

Friction and Tribology

“Elastic and Plastic”
Greenwood Williamson – 1966





$\sigma \sim$ 100 nm
R $\sim$ 70 um

$\sigma \sim$ 160 nm
R $\sim$ 10 um

“Elastic Deformation”

“Plastic Deformation”

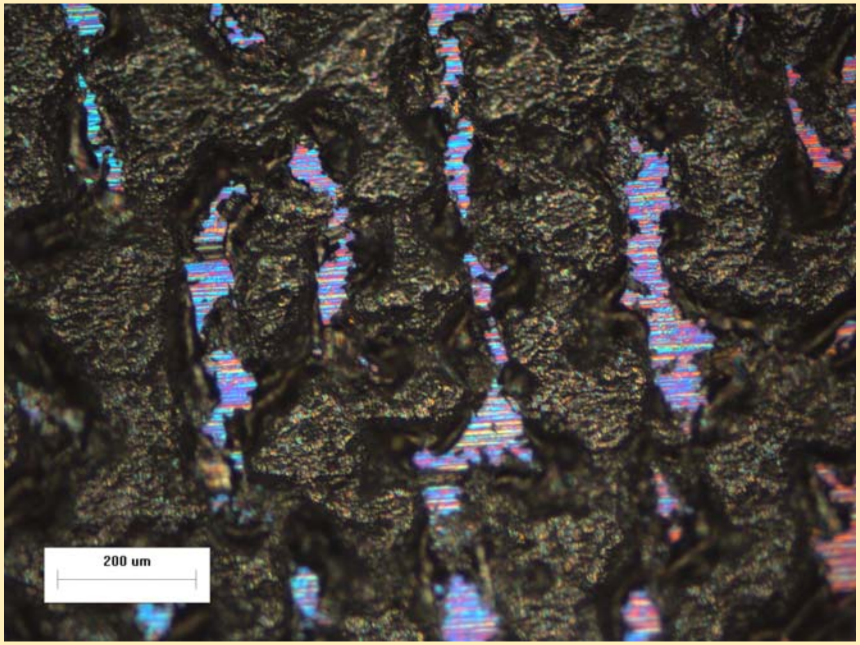
$$\Psi = \left(\frac{E^*}{H}\right)\left(\frac{\sigma}{R}\right)^{\frac{1}{2}}$$

Courtesy of Dr. Don Cohen at MI Metrology, LLC www.michmet.com

Experiment

Residual Surface Texture from Horn

Apparent Area = 70% of image



Peeled Surface

Real Area = 30% of image

A_r/A_{app} = ~ 42%

Charpy Impact

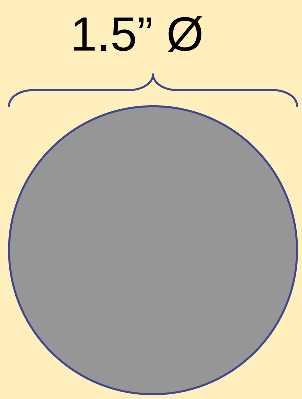
- monolithic100 % laminar

  50% laminar, notched

  laminate

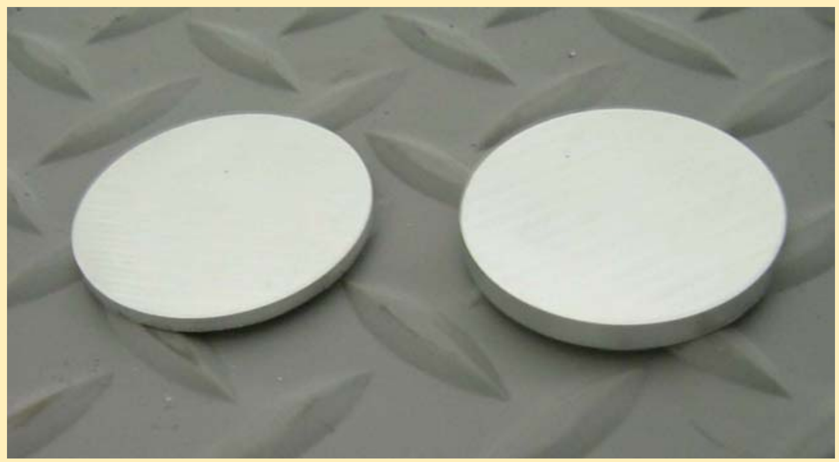
monolithic		
100% laminate		
50% laminate over bulk		

High Speed Impact testing



Target Thickness = 0.16”

Flyer Thickness = 0.08”



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Spall strength measurements

specimens to be tested by ARL

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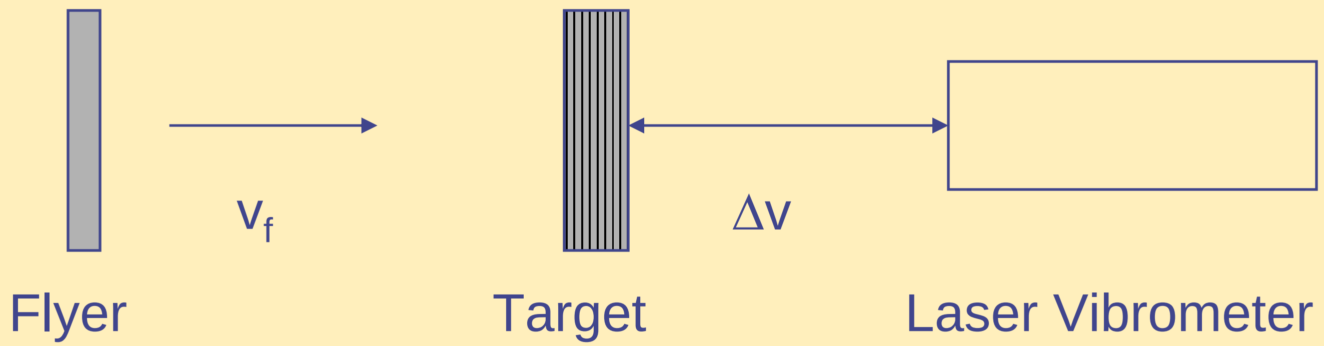


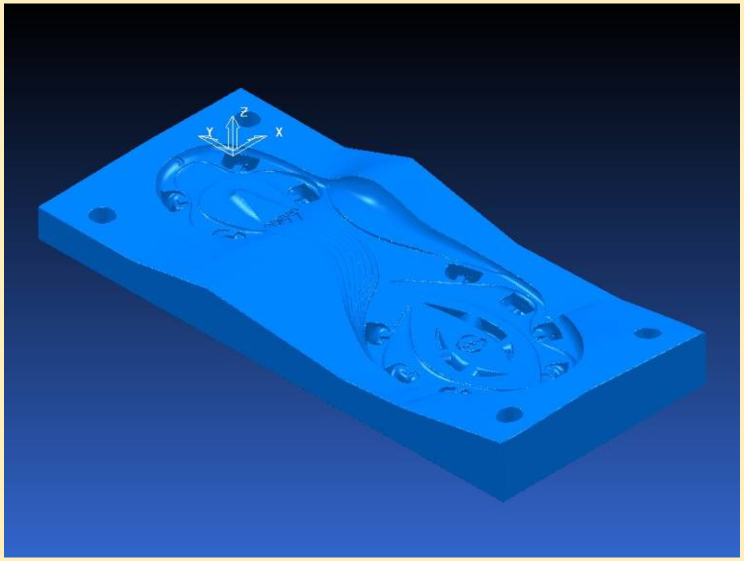
$$\sigma \propto C_{eff} \Delta v$$

$$C_{eff} \approx \sqrt{\frac{E}{\rho}}$$

Current Geometry Limitations

Prototype Parts Present Unique Challenges

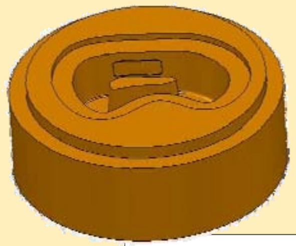
- The UC process currently has geometry limitations related to tall thin features and overhangs…



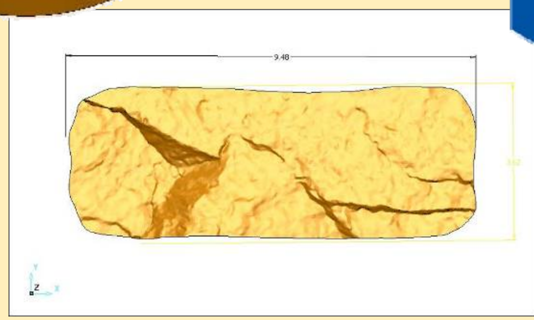
Great Part!

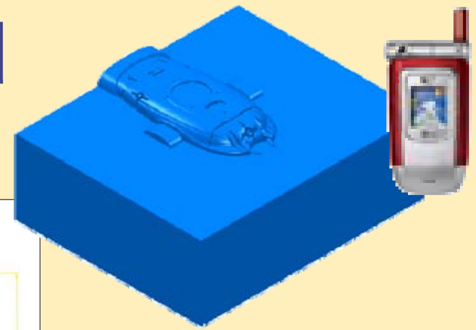
Challenging Part!

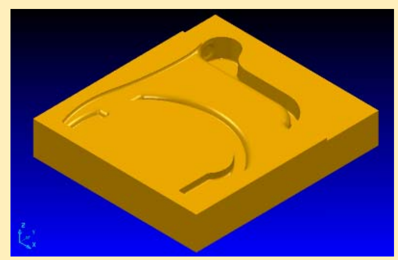
Other Examples



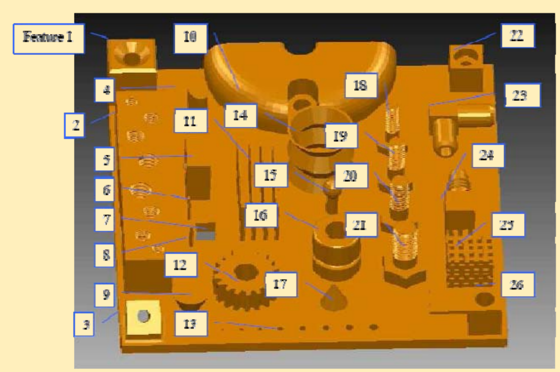
Good







Bad



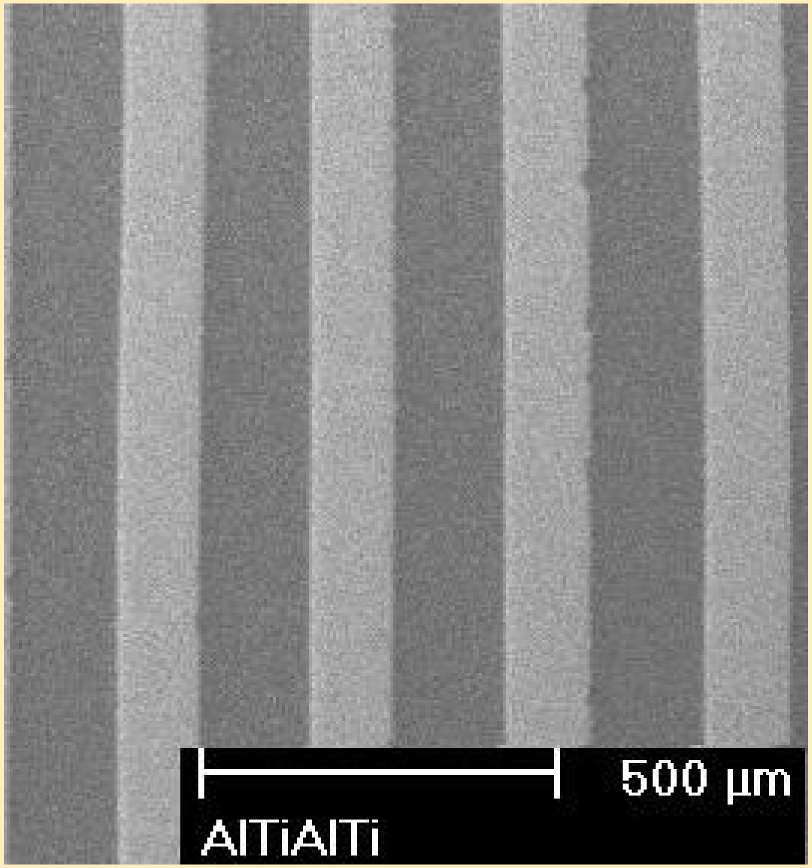
CAD Image of TBE Benchmark Part 1

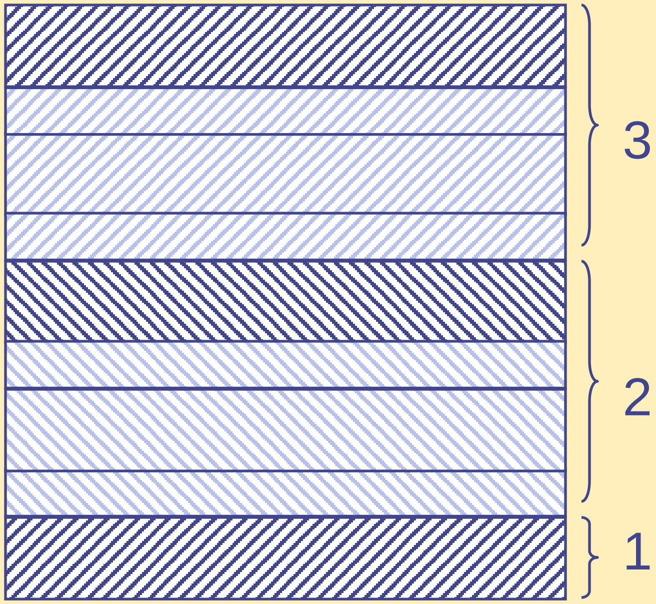
High Aspect Ratio Features and Overhangs

- High Aspect ratios: feature resonance makes relative motion impossible – no consolidation
- Overhangs: Compressive loads are required to produce bonds – support material required
- Appropriate support materials address both issues

Other Applications

Al-Ti laminates





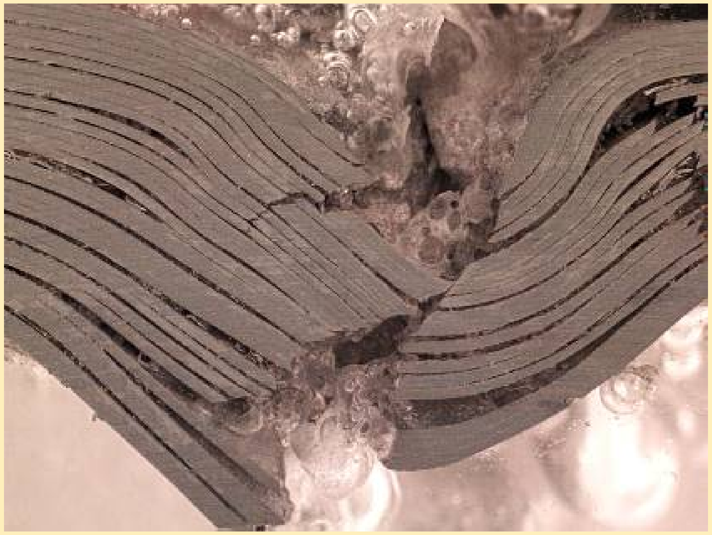
Procedure

- **Weld Ti to Al 3003 Substrate**
- **Weld a sandwich of Ti/1100/ 3003/1100 onto Ti**
- **Repeat**
- **0.004” layers**

Engineered Materials

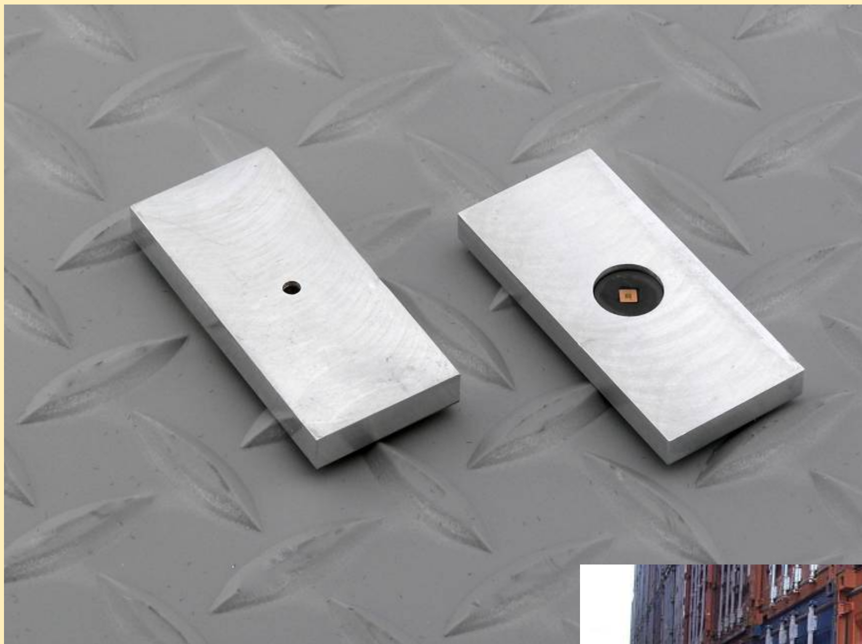
- Materials with thermally sensitive/metastable microstructures are well suited to additive manufacturing with this process
- 5083 cryo-milled nano-grained Al example
- Materials with specialized mechanical or physical properties

Nano grained 5083 Al laminate with 1100 Al inter-layer



Ballistic specimen

Embedded RFID



- RFID embedded directly in parts
- Rugged RFID tags also used as bolt on’s
- Two way
- Data storage

Embedded Sensors

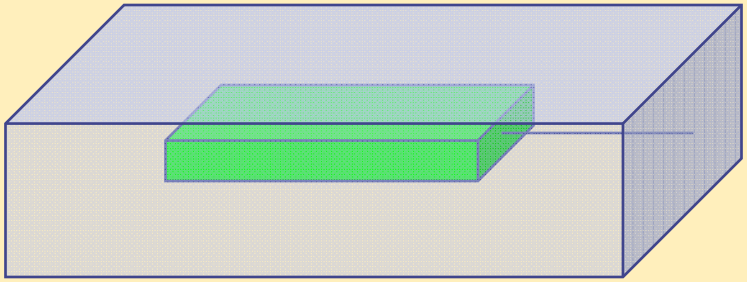
- Rugged wireless sensors embedded directly within vehicle components.
- Can be “grown” on existing fielded components.

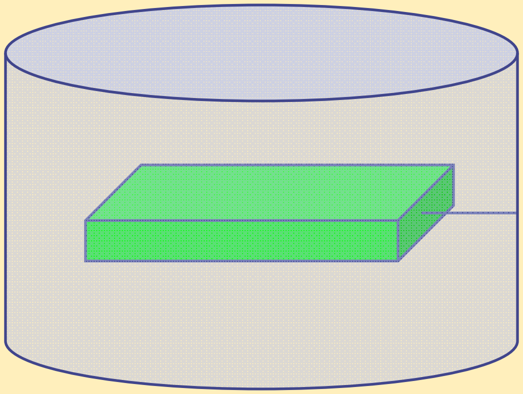
Shots Fired/Received Sensor

Planetary Temperature Sensor

Advanced Engine Sensors

Tamper Proof Electronics

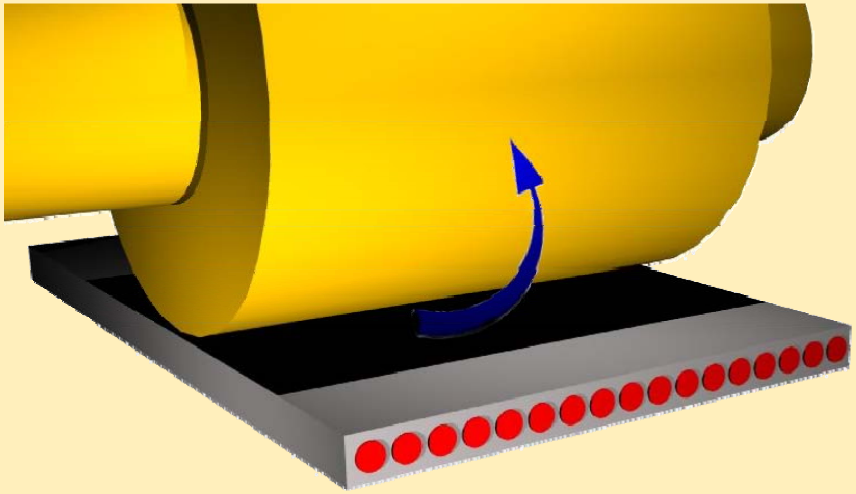


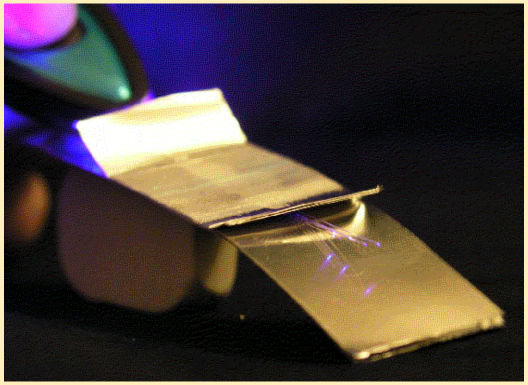


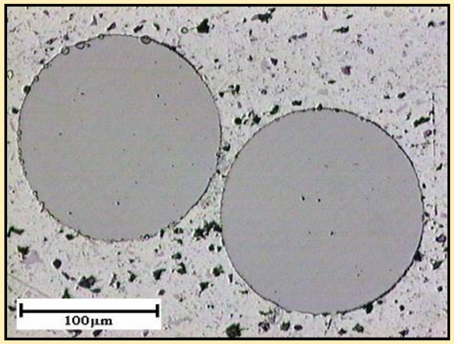
- Electronics embedded directly within metal matrix.
- No seams
- No lids
- No screws
- Tamperproof sensors detect invasion

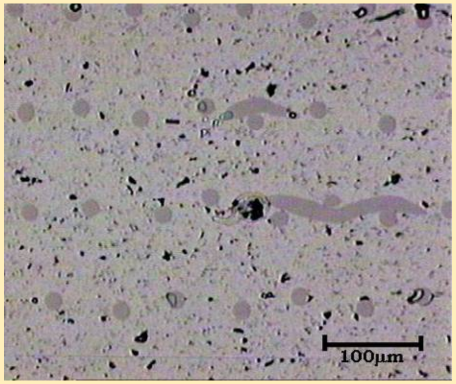
Fiber Embedding Options

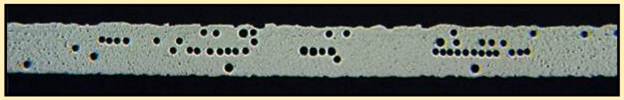
- Wide variety of reinforcing and sensor-based fibers can be safely embedded:
  - MMC technology
  - Fiberoptic sensors
  - Component "patch" repair



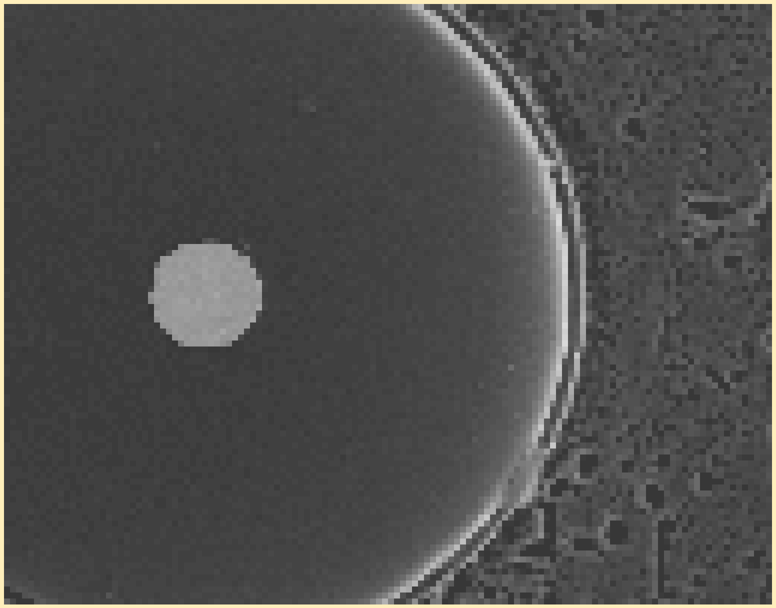




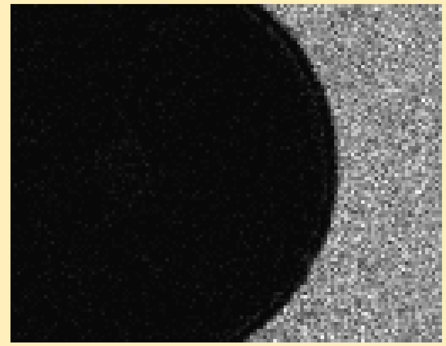




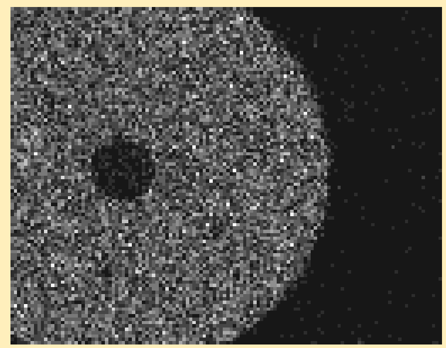
Elemental Mapping



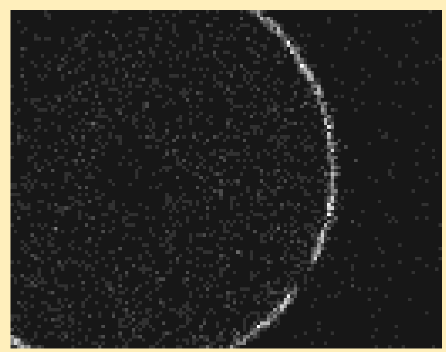
- No trace of interfacial reaction.
- No reaction zone which may weaken the composite.



Al, 44



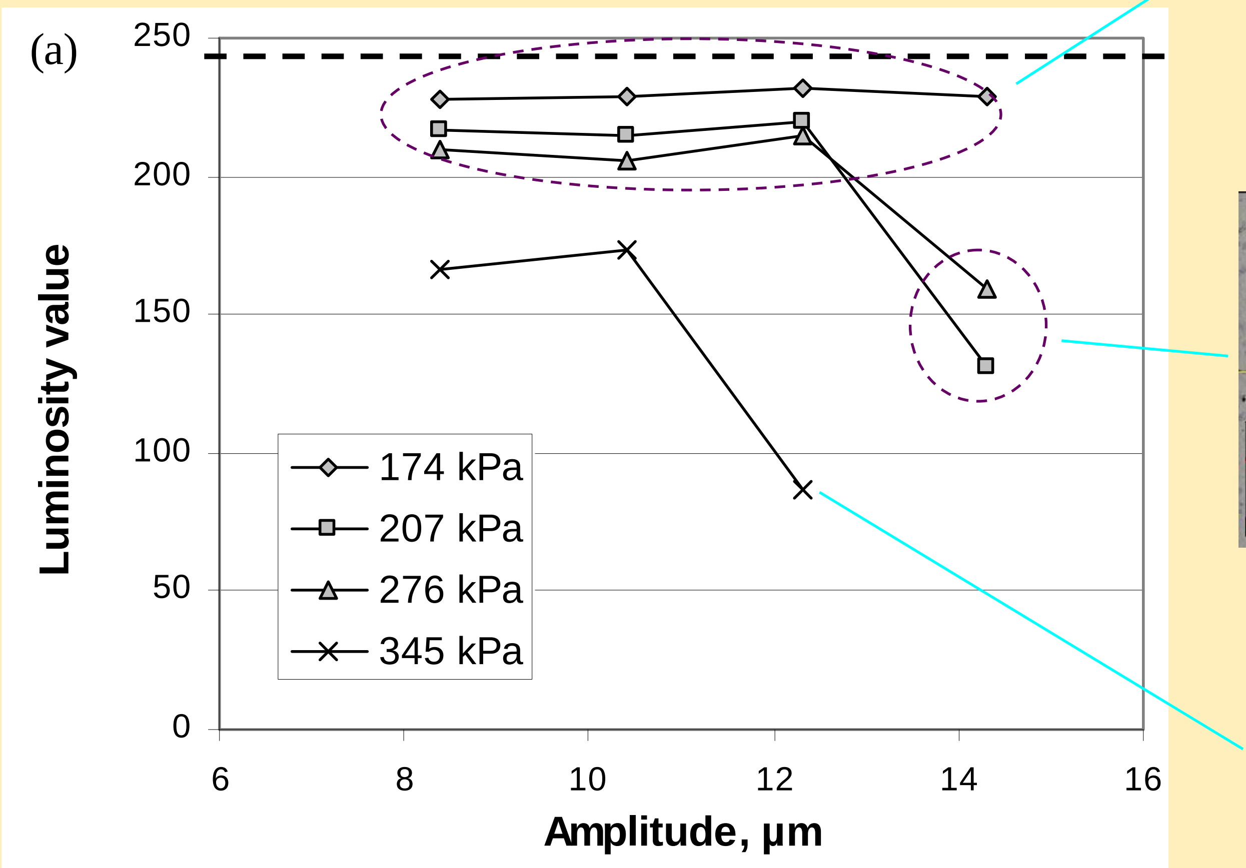
Si, 11

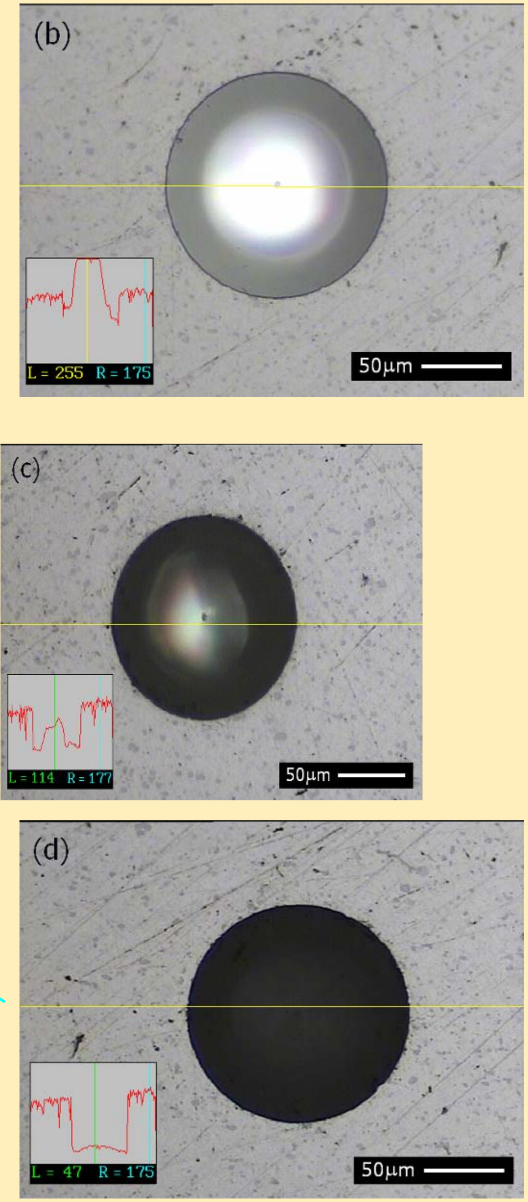


C, 16

Luminosity Responses

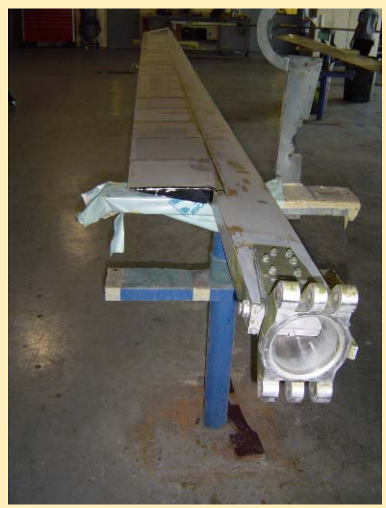
- Coating removed prior to consolidation
- Control fiber luminosity

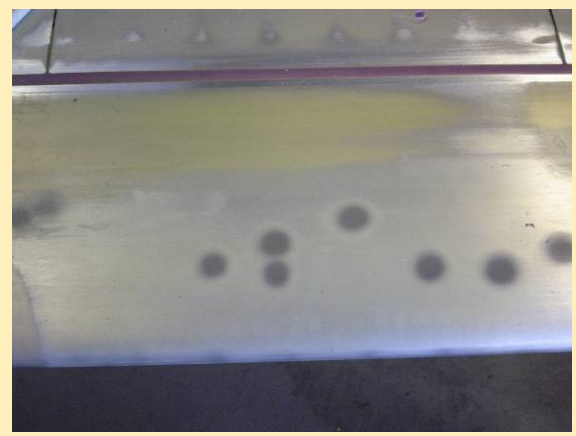




Feature Restoration

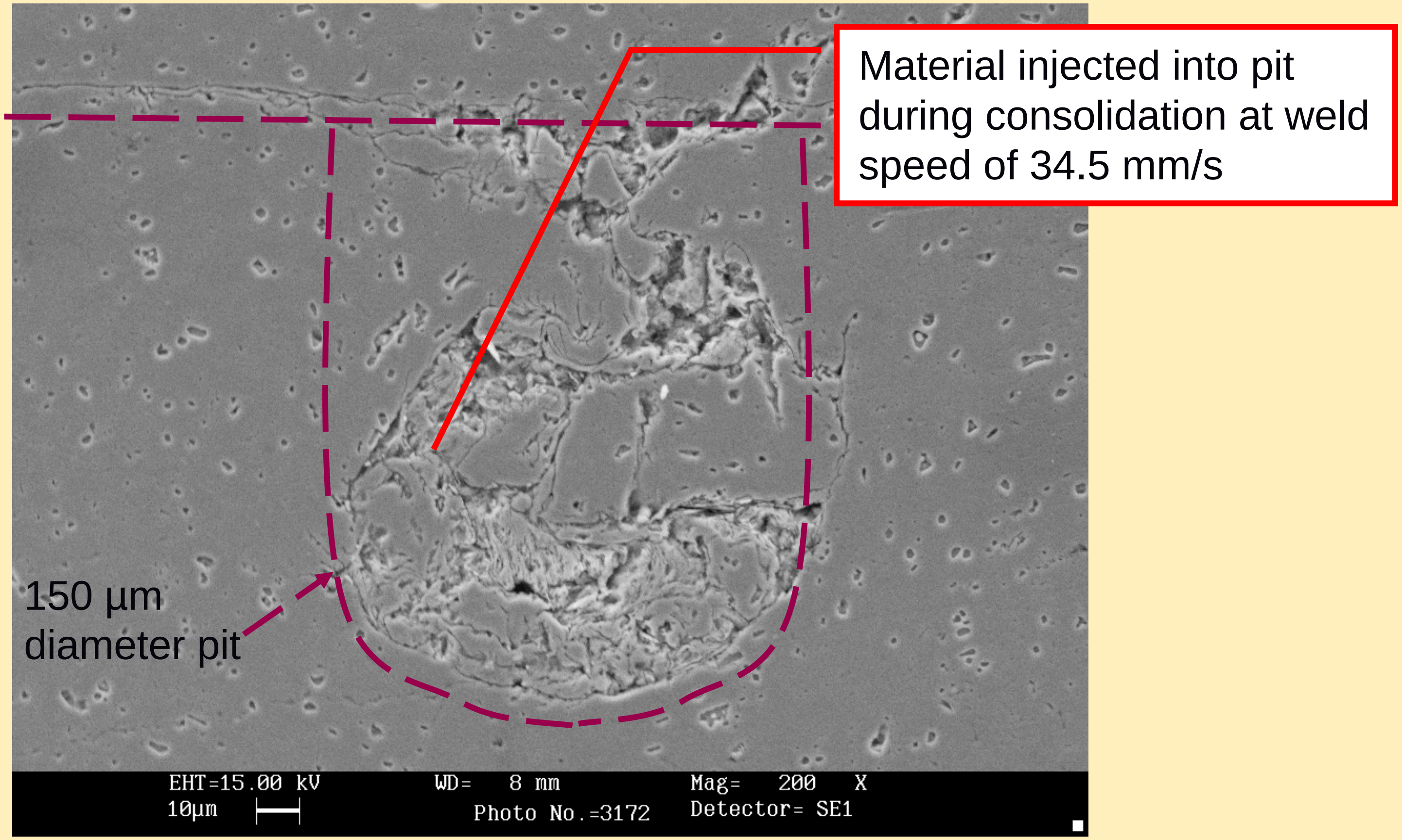
- Repair out of tolerance components that have no repair method or replacement supply base.
- Reinforce repair with fibers and/or multiple materials





Feature Restoration

- Ultrasonic plasticity also can fill micro cracks for further repair quality.



Summary

- UC process is commercialized for aluminum tooling applications
- Properties data available to date is limited due to existing customer needs
  - Working with aerospace and defense customers to expand
- Many novel advanced structure application opportunities

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